Verification of a bioclimatic modeling system in a growing suburb in Melbourne

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Title: Verification of a bioclimatic modeling system in a growing suburb in Melbourne

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Corresponding Author: Dr. Elmira Jamei, Ph.D

Corresponding Author's Institution: Victoria University

First Author: Elmira Jamei, Ph.D

Order of Authors: Elmira Jamei, Ph.D; Mehdi Seyedmahmoudian, PhD; Ben Horan, PhD; Alex Stojcevski, PhD

Abstract: Urban climate knowledge has been increasingly integrated into urban design and planning practices. Numerical modeling systems, such as climatic and bioclimatic tools, are currently more popular than onsite field measurements. This higher popularity is mainly due to the complicated interactions in 3D urban environments and the spatial distribution of various climatic parameters that cannot be captured thoroughly via on-site measurements alone. Such modeling systems also offer better solutions to overcome the nonlinearity of urban climate in forecasting different "what if scenarios."
This paper provides an overview of different types of climatic and bioclimatic modeling systems and presents their main benefits and shortcomings. In the second part of this study, one of the most commonly used tools in urban climate studies, namely, ENVI-met, was selected, and its reliability in different contexts was investigated by reviewing past researches. The applicability of ENVI-met in accurately simulating the influence of future urban growth on one of the fastest growing suburbs in Melbourne, was tested by conducting a sensitivity analysis on inputs and control parameters, backed up with a series of field measurements in selected points. RMSE value was calculated for different runs of the initial ENVI-met model with adjusted control parameters (e.g., factor of short-wave adjustment, initial air temperature, relative humidity, roughness length, wind speed, albedo of walls, and albedo of roofs). The model achieved the optimum performance by altering the short-wave adjustment factor from 0.5 to 1; therefore, ENVI-met was considered a reliable tool for relative comparison of urban dynamics. The findings of this study not only help planners select the most practical modeling systems that address project objectives but also educate them on limitations associated with using ENVI-met.

Response to Reviewers: Answers to Editor's Comments

Q. in the abstract, add your own quantitative results.

A. The abstract includes further details in the revised manuscript; e.g., the background, objectives, method, final quantitative results and future implications.

"Urban climate knowledge has been increasingly integrated into urban design and planning practices. Numerical modeling systems, such as climatic and bioclimatic tools, are currently more popular than onsite field measurements. This higher popularity is mainly due to the complicated interactions in 3D urban environments and the spatial distribution of various climatic parameters that cannot be captured thoroughly via on-site measurements alone. Such modeling systems also offer better solutions to overcome the nonlinearity of urban climate in forecasting different "what if scenarios."
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Q. From the introduction, move your new additions (This paper provides an overview of different types of climatic and bioclimatic modelling systems and briefly presents their main benefits and shortcomings in calculations first. One of the most comprehensive tools among climatic and bioclimatic modelling systems (ENVI-met) was selected and thoroughly explored through a comprehensive review on the past researches.
In the second part of the paper, the reliability of ENVI-met as one of the most popular bioclimatic tools is discussed in one of the fastest growing suburbs in Melbourne, Australia by conducting field measurements) to the end of the introduction, and explain the international context justifying the need for your work.
A. The paragraph has been moved to the end of introduction and the significance of conducting such studies in international context has been thoroughly explained as below:

"Nowadays, Climatic and bioclimatic modeling systems are increasingly being used to highlight the benefits of heat mitigation strategies in urban areas (e.g., use of green infrastructure, alterations on urban form and street geometry, and application of high-albedo materials). However, testing the reliability of the computational models are necessary before evaluating the effectiveness of heat mitigation scenarios. Although several previous studies have conducted limited assessment of a range of climatic and bioclimatic modeling systems for different contexts with diverse geographical and climatic backgrounds, systematic evaluation of

the models and their sensitivity to inputs and control parameters remains lacking. Whether the previous studies on model validation in one part of the world provide any assurance that the model can accurately simulate the effects of heat mitigation scenarios in the other parts of the world remains unclear.
Therefore, this study aims to provide an overview of different types of climatic and bioclimatic modeling systems and briefly present their main benefits and shortcomings in calculations initially. In the second part of this study, one of the most comprehensive and widely used modeling systems, namely, ENVI-met, was selected, and its reliability in different contexts was investigated by reviewing past researches. A sensitivity analysis on inputs and control parameters was then conducted, in line with field measurements in selected areas, to test the applicability of ENVI-met in accurately simulating the influence of future urban growth on one of the fastest growing suburbs in, Melbourne".

Q. Add a methodological section
A. An introduction to the methodology section and what is covered in each part has been added to the methodology section as below:

"In this section, one of the fastest growing suburbs in Melbourne that will be the subject of rapid urban development in the future is studied. One of the visions of Melbourne City Council for future urban developments is to quantify the thermal and climatic consequences of implementing the proposed urban growth scenarios. Therefore, this section explains the validation process for the model that will be used as the base for future urban growth scenarios and assess the reliability of ENVI-met in accurately modeling simulated outputs.
The methodology section is divided into two parts. In the first section, description of the study area, selection of measurement points and their physical characteristics, process of field measurements, equipment used to conduct field measurements, and monitored values are explained. The second part discusses the simulation approach, the establishment of the model with accurate inputs and configuration parameters, and the comparison of the results of the simulated and measured values through RMSE calculation. Finally, the validation process of the model and the adjustments needed for the control parameters are described."

Q. - limit the total number of figures/tables to max 10.
A. The number of the Tables has been reduced from 17 to 10 in the revised manuscript. Currently, there are 10 Figures and 10 Tables in the revised manuscript:
List of removed Tables are:
Table 1
Table 2
Table 5
Table 8
Table 9
Table 10
Table 11

The information and content of some the Tables are now included in the body of the manuscript (e.g., Table 1 and 2)

Q. Ask your supervisor for a serious revision of your manuscript

A. The manuscript is revised, and the quality of English language has been further improved to meet the criteria of the 'Science of Total Environment Journal'.

Answers to Reviewer 3 Comments

Q. Most of the comments have been adequately responded to. The main limitation is the lack of discussion (referring back to the literature) in relation to the field observation part of the paper. This was mentioned in my previous review. I think it would be useful to add a paragraph or two in response to this.

A. A section on the comparison between the findings of this paper and the previous studies in relation to the difference found between the observed and simulated values is added to the discussion part of the paper as below:

"The results of this study showed that although ENVI-met is widely used to address the questions of the influence of urban development on urban climate, pedestrian thermal comfort, surface, and air temperature, few studies have explored the limitations associated with the use of software with regard to the sensitivity of the model to different control and input parameters and scale sensitivity analysis.
In this study, we used measured versus simulated error metrics to test the reliability of ENVI-met in predicting air temperature values. The findings of this work were in line with those of the studies that have found that reliance on the error metric alone without including the sensitivity of the model to its own input parameters would result in higher EMSE values and therefore less accuracy in the simulated outputs [78-81]. This work also confirmed the findings of the studies that have found that the main ENVI-met limitation is the performance of the model in relation to the heat transfer between buildings and atmosphere; therefore, further rigorous and comprehensive testing and verifications of this numerical modeling system are required [82, 83]. The results of this study also verified the concerns indicated by [84] in relation to the correct wind profile in the model configuration file to prevent the model from crashing caused by turbulence due to the vertical motion at the beginning of running the model. This study highlighted the necessity to work on the wind profiles in ENVI-met that could represent the fluctuations and variations in the prevailing wind pattern, which are common in urban areas. These limitations were also identified by [85] and must be reacknowledged as the potential improvement to ENVI-met as a sophisticated urban climate modeling system. "

Dear Editor;

We would like to thank you for the constructive feedbacks and submit the revised manuscript "**Verification of a bioclimatic modeling system in a growing suburb in Melbourne**" for your consideration for publication in the journal of "**Science of the Total Environment**".

All Authors have seen and approved the manuscript being re-submitted. We warrant that the article is the Authors' original work and has not received prior publication and is not under consideration for publication elsewhere. On behalf of all Co-Authors, the corresponding Author I bear full responsibility for the submission.

We believe that this manuscript is important, because climate change poses a fundamental threat to our environment and humans. Given the increasing number of hot days in many parts of the world, (specially in pacific regions), role of urban designers in heat mitigation and adaptation and their knowledge in integrating urban climate in design practices are becoming more critical.

Thank you for your kind consideration.
Yours Sincerely;

Dr Elmira Jamei
PhD (Deakin), M.Sc(Hons)(UTM), B.Arch.Eng (Hons)(QAI)
Course Chair & Lecturer|Building Design
Deputy Director Research Infrastructure & Built Environment ISILC
College of Engineering and Science
Victoria University, Melbourne, Victoria, Australia
Tel: +61 3 99195847|Office: D530C

Title Page

Title: ~~The verification study~~ Verification of a bioclimatic ~~modelling~~modeling system in a growing suburb in Melbourne

Abstract

~~Nowadays, urban climatic science~~Urban climate knowledge has been increasingly integrated into urban design and planning ~~works~~practices. ~~Nowadays, nN~~Numerical modeling systems~~, such as~~~~such as~~, such as climatic and bioclimatic tools, are currently more popular ~~for~~ than onsite field measurements. This higher popularity is mainly due to the complicated interactions in ~~three-dimensional~~3D urban environments and the spatial distribution of various climatic parameters that cannot be ~~included~~ captured thoroughly ~~in~~ ~~through~~ via on-site ~~field~~ measurements alone. ~~Furthermore, nNumerical~~ Such modeling systems ~~are also great tools~~also offer better solutions ~~for~~ to ~~overcoming~~ overcome the ~~non-~~nonlinearity of urban climate ~~and~~ in forecasting different "what if scenarios."

This paper provides an overview of different types of climatic and bioclimatic ~~modelling~~modeling systems and presents their main benefits and shortcomings. In the second part of this study, one of the most commonly used tools in urban climate studies, namely, ~~(~~ENVI-met~~)~~, was selected, and its reliability in different contexts was investigated ~~through~~ by reviewing ~~the~~ past ~~researches~~ researches. ~~Then, the~~ The applicability of ENVI-met in accurately simulating the ~~impact~~ influence of future urban growth ~~in~~on one of the fastest growing ~~cities in Pacific regions, specifically~~suburbs in ~~(~~Melbourne~~)~~, was tested ~~through~~ by conducting a sensitivity analysis on ~~the~~ inputs and control parameters, backed up with a series of field measurements in ~~the~~ selected points. RMSE value was calculated for different runs of the initial ENVI-met model with adjusted control parameters (e.g., ~~Factor~~ factor of short-wave adjustment, ~~Initial~~ initial air temperature, ~~Relative~~ relative humidity, ~~Roughness~~ roughness length, ~~Wind~~ wind speed, ~~Albedo~~ albedo of walls, and ~~Albedo~~ albedo of roofs). The model achieved the optimum performance by altering the short-wave adjustment factor from 0.5 to 1; ~~and~~ therefore, ENVI-met was considered ~~as~~ a reliable tool for relative comparison of urban dynamics. The findings of this study not only help planners ~~to not only~~ select the most practical ~~modelling~~modeling systems that address ~~the~~ project objectives~~,~~ but also educate them on limitations associated with using ENVI-met ~~(one of the most commonly used tools in urban climate studies)~~.

Comment [16151]: We removed this to avoid redundancy.

~~This paper provides a summary of different types of climatic and bioclimatic modeling systems and briefly presents their main benefits and shortcomings in calculations. The reliability of ENVI-met as one of the most popular bioclimatic tools is also discussed by providing a comprehensive review of previous validation studies and by conducting a field measurement in one of the fastest growing suburbs in Melbourne, Australia to validate ENVI-met modeling. Finally, the limitations of ENVI-met (different versions) are discussed to assist planners in carefully selecting modeling systems that can accurately address the aims and objectives of their project.~~

Key words: Urban ~~planning~~ Planning, Urban Design, Climatic and Bioclimatic Modeling Systems, ENVI-met, Urban Climate

Authors:

Elmira Jamei, College of Engineering and Science, Victoria University, Melbourne VIC 3011, Victoria, Australia; elmira.jamei@vu.edu.au

Mehdi Seyedmahmoudian, School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne VIC 3122, Victoria, Australia; mseyedmahmoudian@swin.edu.au

Ben Horan, School of Engineering, Deakin University, Geelong VIC 3216, Victoria, Australia; ben.horan@deakin.edu.au

Alex Stojcevski, School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne VIC 3122, Victoria, Australia; astojcevski@swin.edu.au

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Urban climate knowledge has been increasingly integrated into urban design and planning practices. Numerical modeling systems, such as climatic and bioclimatic tools, are currently more popular than onsite field measurements. This higher popularity is mainly due to the complicated interactions in 3D urban environments and the spatial distribution of various climatic parameters that cannot be captured thoroughly via on-site measurements alone. Such modeling systems also offer better solutions to overcome the nonlinearity of urban climate in forecasting different "what if scenarios."

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Key words: Urban Planning, Urban Design, Climatic and Bioclimatic Modeling Systems, ENVI-met, Urban Climate

Authors:

Elmira Jamei, College of Engineering and Science, Victoria University, Melbourne VIC 3011, Victoria, Australia; elmira.jamei@vu.edu.au

Mehdi Seyedmahmoudian, School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne VIC 3122, Victoria, Australia; mseyedmahmoudian@swin.edu.au

Ben Horan, School of Engineering, Deakin University, Geelong VIC 3216, Victoria, Australia; ben.horan@deakin.edu.au

Alex Stojcevski, School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne VIC 3122, Victoria, Australia; astojcevski@swin.edu.au

***Responses to Reviewers Comments**

Answers to Editor's Comments	
1	Q. in the abstract, add your own quantitative results.
1	A. The abstract includes further details in the revised manuscript; e.g., the background, objectives, method, final quantitative results and future implications. ***"Urban climate knowledge has been increasingly integrated into urban design and planning practices. Numerical modeling systems, such as climatic and bioclimatic tools, are currently more popular than onsite field measurements. This higher popularity is mainly due to the complicated interactions in 3D urban environments and the spatial distribution of various climatic parameters that cannot be captured thoroughly via on-site measurements alone. Such modeling systems also offer better solutions to overcome the nonlinearity of urban climate in forecasting different "what if scenarios."*** ***This paper provides an overview of different types of climatic and bioclimatic modeling systems and presents their main benefits and shortcomings. In the second part of this study, one of the most commonly used tools in urban climate studies, namely, ENVI-met, was selected, and its reliability in different contexts was investigated by reviewing past researches. The applicability of ENVI-met in accurately simulating the influence of future urban growth on one of the fastest growing suburbs in Melbourne, was tested by conducting a sensitivity analysis on inputs and control parameters, backed up with a series of field measurements in selected points. RMSE value was calculated for different runs of the initial ENVI-met model with adjusted control parameters (e.g., factor of short-wave adjustment, initial air temperature, relative humidity, roughness length, wind speed, albedo of walls, and albedo of roofs). The model achieved the optimum performance by altering the short-wave adjustment factor from 0.5 to 1; therefore, ENVI-met was considered a reliable tool for relative comparison of urban dynamics. The findings of this study not only help planners select the most practical modeling systems that address project objectives but also educate them on limitations associated with using ENVI-met".***
2	Q. From the introduction, move your new additions (This paper provides an overview of different types of climatic and bioclimatic modelling systems and briefly presents their main benefits and shortcomings in calculations first. One of the most comprehensive tools among climatic and bioclimatic modelling systems (ENVI-met) was selected and thoroughly explored through a comprehensive review on the past researches. In the second part of the paper, the reliability of ENVI-met as one of the most popular bioclimatic tools is discussed in one of the fastest growing suburbs in Melbourne, Australia by conducting field measurements) to the end of the introduction, and explain the international context justifying the need for your work.
2	A. The paragraph has been moved to the end of introduction and the significance of conducting such studies in international context has been thoroughly explained as below: ***"Nowadays, Climatic and bioclimatic modeling systems are increasingly being used to highlight the benefits of heat mitigation strategies in urban areas (e.g., use of green infrastructure, alterations on urban form and street geometry, and application of high-albedo materials). However, testing the reliability of the computational models are necessary before evaluating the effectiveness of heat mitigation scenarios. Although several previous studies have conducted limited assessment of a range of climatic and bioclimatic modeling systems for different contexts with diverse geographical and climatic backgrounds, systematic evaluation of the models and their sensitivity to inputs and control parameters remains lacking. Whether the previous studies on model validation in one part of the world provide any assurance that the model can accurately simulate the***

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3	Q. Add a methodological section
3	A. An introduction to the methodology section and what is covered in each part has been added to the methodology section as below: ***"In this section, one of the fastest growing suburbs in Melbourne that will be the subject of rapid urban development in the future is studied. One of the visions of Melbourne City Council for future urban developments is to quantify the thermal and climatic consequences of implementing the proposed urban growth scenarios. Therefore, this section explains the validation process for the model that will be used as the base for future urban growth scenarios and assess the reliability of ENVI-met in accurately modeling simulated outputs.*** ***The methodology section is divided into two parts. In the first section, description of the study area, selection of measurement points and their physical characteristics, process of field measurements, equipment used to conduct field measurements, and monitored values are explained. The second part discusses the simulation approach, the establishment of the model with accurate inputs and configuration parameters, and the comparison of the results of the simulated and measured values through RMSE calculation. Finally, the validation process of the model and the adjustments needed for the control parameters are described."***
4	Q. - limit the total number of figures/tables to max 10.
4	A. The number of the Tables has been reduced from 17 to 10 in the revised manuscript. ***Currently, there are 10 Figures and 10 Tables in the revised manuscript:*** ***List of removed Tables are:*** ***Table 1*** ***Table 2*** ***Table 5*** ***Table 8*** ***Table 9*** ***Table 10*** ***Table 11*** ***The information and content of some the Tables are now included in the body of the manuscript (e.g., Table 1 and 2)***
5	Q. Ask your supervisor for a serious revision of your manuscript
5	A. ***The manuscript is revised, and the quality of English language has been further improved to meet the criteria of the 'Science of Total Environment Journal'.***
	Answers to Reviewer 3 Comments
1	Q. Most of the comments have been adequately responded to. The main limitation is the lack of discussion (referring back to the literature) in relation to the field observation part of the paper. This was mentioned in my previous review. I think it would be useful to add a

	paragraph or two in response to this.
1	A. A section on the comparison between the findings of this paper and the previous studies in relation to the difference found between the observed and simulated values is added to the discussion part of the paper as below: ***"*The results of this study showed that although ENVI-met is widely used to address the questions of the influence of urban development on urban climate, pedestrian thermal comfort, surface, and air temperature, few studies have explored the limitations associated with the use of software with regard to the sensitivity of the model to different control and input parameters and scale sensitivity analysis.** **In this study, we used measured versus simulated error metrics to test the reliability of ENVI-met in predicting air temperature values. The findings of this work were in line with those of the studies that have found that reliance on the error metric alone without including the sensitivity of the model to its own input parameters would result in higher EMSE values and therefore less accuracy in the simulated outputs [78-81]. This work also confirmed the findings of the studies that have found that the main ENVI-met limitation is the performance of the model in relation to the heat transfer between buildings and atmosphere; therefore, further rigorous and comprehensive testing and verifications of this numerical modeling system are required [82, 83]. The results of this study also verified the concerns indicated by [84] in relation to the correct wind profile in the model configuration file to prevent the model from crashing caused by turbulence due to the vertical motion at the beginning of running the model. This study highlighted the necessity to work on the wind profiles in ENVI-met that could represent the fluctuations and variations in the prevailing wind pattern, which are common in urban areas. These limitations were also identified by [85] and must be reacknowledged as the potential improvement to ENVI-met as a sophisticated urban climate modeling system. "**

Introduction~~: Modelling and measurement approaches~~

The importance of climatic ~~modelling~~modeling as a powerful planning tool has been regularly highlighted in the literature over the last few decades because of rapid urbanization rate, global climate change, and increased heat~~-~~ wave rate [1]. As a result, climatic and bioclimatic ~~modelling~~modeling systems have been increasingly ~~employed~~ used to achieve the objectives of climate-sensitive urban planning.

~~This paper provides an overview of different types of climatic and bioclimatic modelling systems and briefly presents their main benefits and shortcomings in calculations first. One of the most comprehensive tools among climatic and bioclimatic modelling systems (ENVI-met) was selected and thoroughly explored through a comprehensive review on the past researches.~~

~~In the second part of the paper, the reliability of ENVI-met as one of the most popular bioclimatic tools is discussed in one of the fastest growing suburbs in Melbourne, Australia by conducting field measurements.~~

The popularity of numerical ~~modelling~~modeling for on-site field measurements has led to increased research interest in ~~modelling~~modeling approaches [2]. This popularity is justified by the high capacity of climatic ~~modelling~~modeling ~~in dealing~~to ~~deal with~~ handle the complexities and nonlinearity of urban climate systems. ~~Furthermore, climatic~~Climatic ~~modelling~~modeling systems also enable researchers to have greater control over ~~modelling~~modeling compared with ~~non-~~nonlinear on-site field measurements. Most importantly, these ~~modelling~~modeling systems are economically viable and efficient in saving time and resources [3-5]. ~~Modelling~~Modeling approaches can forecast and predict the climatic effects of diverse “what-if” scenarios,~~”~~ ~~thereby leading~~ which leads to an environmentally friendly planning scheme and an improved outdoor thermal environment for citizens [6].

On-site field measurement is a time-consuming approach that can only cover a limited number of parameters at a time. The complex interactions of 3D urban spaces and the spatial distribution of climatic parameters cannot be included simultaneously by conducting field measurements [7, 8]. However, on-site measurements are an integral part of any ~~modelling~~modeling approach due to the importance of model validation.

Nowadays, ~~climatic~~ Climatic and ~~bioclimatoe~~ bioclimatic modeling systems are increasingly being used to highlight the benefits of heat mitigation strategies in urban areas (e.g., use of green infrastructure, alterations on urban form and street geometry, and application of high-~~-~~albedo materials). However, ~~there is a significant need to invest on~~ testing ~~and validating~~the reliabikity of the computational models ~~used to conduct the simulations,~~ are ~~required~~ necessary before evaluating the effectiveness of heat mitigation scenarios. ~~While~~Although ~~some~~

several previous studies have conducted limited assessment of a range of climatic and bioclimatic modeling systems for different contexts with diverse geographical and climatic backgrounds, ~~there is still a lack in the~~ systematic evaluation of the models and their sensitivity to ~~the~~ inputs and control parameters remains lacking. ~~Additionally, it is still unclear whether~~ Whether the previous studies on model validation in one part of the world~~,~~ provide any assurance that the model can accurately simulate the ~~impact~~ effects of heat mitigation scenarios in the other parts of the world remains unclear.

Therefore, this study aims to provide an overview of different types of climatic and bioclimatic ~~modelling~~modeling systems and briefly ~~presents~~ present their main benefits and shortcomings in calculations ~~first~~initially. In the second part of this study, one of the most comprehensive and widely used ~~modelling~~modeling systems, namely, ~~(~~ENVI-met~~)~~, was selected, and its reliability in different contexts was investigated ~~through~~ by reviewing ~~the~~ past ~~researches~~ researches. ~~Then, to test the applicability of ENVI-met in accurately simulating the impact of future urban growth in one of the fastest growing cities in Pacific regions (Melbourne), a~~A sensitivity analysis on inputs and control parameters ~~were~~was then conducted, in line with field measurements in ~~the~~ selected areas, to test the applicability of ENVI-met in accurately simulating the ~~impact~~ influence of future urban growth on one of the fastest growing suburbs in~~cities in Pacific regions~~, ~~specifically~~ ~~(~~Melbourne~~)~~.

Literature ~~Review~~review

Climatic ~~modelling~~modeling systems

Urban climate models are defined ~~based~~ on the basis of their scales, which range from a few ~~centimetres~~centimeters to hundreds of ~~kilometres~~kilometers. ~~Climatic models are classified into~~ The five groups of climatic models based on ~~the~~ scale ~~discussed~~ are ~~(e.g.~~ human-, room-, building-, city block-, and urban-scale models~~)~~ [9]. The scale of ~~the~~ a model defines the resolution of each classification~~.~~, and the resolution of each classification is highly dependent on the model scale.

~~The resolution of each classification is highly dependent on the scale of the model~~ scale~~.~~

Urban scale models often have the largest space resolution [10]. Therefore, planners are highly encouraged to integrate climatic ~~modelling~~modeling systems ~~in which their~~ with a scale ~~ranges to~~ of 1:5,000 m. Only a few climatic ~~modelling~~modeling systems can consider ~~the~~ comprehensive sets of processes (e.g., hydrological, thermal, and energy) due to the long span of time that should be spent on computation and simulation.

Comment [16151]: "Impact" denotes collision. The terms "effect" and "influence," as used in most technical and social science papers, denote the impression of one thing on another.

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~~To address this limitation, scholars have developed models with parameterisationsparameterizations and simplifications, such as simple turbulence calculation [11, 12].~~

To address this limitation, scholars have developed models with parameterizations and simplifications, such as simple turbulence calculation [11, 12]. Some of these models target the hydrological, thermal, and energy processes at the building scale. These models are established at three levels, namely, 1D, 2D, and 3D levels, and are designed for specific circumstances [13]. Oke introduced 1D urban canyon models and suggested that they are primary numerical models that work ~~based~~ on the basis of the energy balance of buildings [14]. Furthermore, 1D models are widely used to assess the microclimate of certain points at urban canyon at the street level. However, spatial differences cannot be detected in calculations because only surface physical properties, such as albedo, moisture level, thermal features, and roughness length, are evaluated. These models underestimate the important role of urban geometry and street orientations [15]. The predefined assumptions in 1D models include horizontally homogeneous flows and temperature fields. However, the main drawback of 1D models is that ~~it simplifies~~ they simplify the turbulence calculation. ~~Additionally, the~~ The spatial differences within a canyon and the role of canyon geometry are also ~~not included~~ excluded in the calculation of energy exchange~~,~~ and in predefined assumptions.

Meanwhile, 2D models adopt certain assumptions in their calculations. ~~Some~~Several assumptions considered in the calculations include predefined city forms and street geometries, rectangular building shapes/heights, dry urban surfaces, zero vegetation coverage, absence of latent heat, and zero heat storage in building materials [16-18].

In the last two decades, 3D models combined with computational fluid dynamics (CFD) have been identified as the strongest tools in climatic ~~modelling~~modeling systems [9]. CFD is based on equations of fluid dynamics and conservation of mass, momentum, and energy [19-21]. Climatic models are associated with CFD and include all radiation, conduction, and physical properties of a complex urban environment during calculation, ~~thereby leading to~~ which results in ~~an~~ accurate calculation [3, 22].

In addition to urban canyon models, mathematical equations derived from field measurements are used to develop context-dependent climatic models [23]. An example of these models is the cluster thermal time constant (CTTC) [24]. ~~Some~~Several climatic models are developed ~~based~~ on the basis of AutoCAD for designers and used to create an accurate 3D urban environment that best represents ~~the~~ a study area [25, 26]. These models have predefined assumptions and values for climatic parameters, such as temperature, mean radiant temperature (Tmrt), and wind speed. ~~Table 1 lists the main drawbacks of each climatic modelling system.~~

~~Table 1. Limitations of different climatic systems [27].~~

~~1 Modelling system~~	~~2 Drawbacks~~
~~3 1D models~~	~~4 Simplified turbulence calculation, spatial differences within a canyon are not considered, role of urban geometry is underestimated in calculation of energy exchange, and predefined assumptions~~
~~5 2D models~~	~~6 Predefined assumptions~~
~~7 CTTC~~	~~8 Developed for certain contexts~~

~~Bio~~ Bioclimatic ~~modelling~~modeling systems

A recently proposed concept in numerical ~~modelling~~modeling systems is the integration of urban climatic knowledge into planning practices [25, 26]. The main task of bioclimatic ~~modelling~~modeling systems is ~~predicting~~ to predict the outdoor ~~human~~ thermal comfort of humans, which is a highly challenging task because of the complexities in calculating radiation fluxes received by a human body from surrounding areas in an urban setting.

RayMan [27] and SOLWEIG [28] are ~~some of the~~ bioclimatic ~~modelling~~modeling systems used by scholars to quantify thermal indices, such as predicted mean vote (PMV) and physiological equivalent temperature (PET). ~~Using~~ The use of these models~~,~~ allows planners ~~can~~ to assess climatic and bioclimatic parameters in urban environments and report accurate values for the outdoor ~~human~~ thermal comfort of humans in complicated outdoor environments. Required output is one of the critical factors in selecting bioclimatic models. For instance, PMV and PET are the required outputs of SOLWEIG and RayMan, ~~leading~~ which leads to the limited use of other thermal indices, such as standard effective temperature (SET), OUT-SET, and universal thermal climate index. Goteborg University [28] established SOLWEIG, which is a radiation model that accurately measures Tmrt and PET through calculations of radiative fluxes received from all directions. However, this model presents limitations, such as ~~using~~the use of a simplified vegetation scheme [29]. ~~One of the main limitations~~ A main limitation of SLOWEIG is that the software uses limited thermal indices in assessing thermal comfort, simplifies the vegetation scheme, calculates radiative fluxes from all directions, and neglects ~~some~~ several climatic parameters ~~affecting~~ that affect comfort.

Fluent is another bioclimatic ~~modelling~~modeling system that incorporates CFD to calculate wind speed and turbulence by considering radiation, heat balance, and evaporation modules [30]. This tool is mainly used to test

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aerodynamics in vehicles or indoor spaces. However, this ~~modelling~~modeling system involves long computation time.

RayMan can calculate radiation in complex urban environments [31]. This model does not require long computation time and can calculate Tmrt; however, the calculation does not include multiple reflections ~~between~~ among buildings. RayMan can also produce a diverse range of heat indices, such as PET and PMV [32]. The main meteorological inputs for RayMan include air temperature, humidity, and wind velocity; building and vegetation information is needed to begin ~~modelling~~modeling computation. RayMan ~~was~~ has been validated in previous studies [32]. In [32], the difference between the ~~modelled~~modeled and measured mean radiation temperatures in a ~~semi-~~semiopen area was found to be negligible (R^2 = 0.95). ~~Some~~ Several studies have reported that RayMan underestimates the value of Tmrt, especially under low solar angles, because it neglects the reflection from ~~the~~ surrounding buildings [33]. The main limitation of this stationary model is that it cannot predict the ~~non-~~nonstationary characteristics of a human body that moves from points A to ~~point~~ B (sunny point to shaded point). ~~The main limitations of~~ In sum, RayMan ~~are listed as;~~has the disadvantages of limited thermal indices in assessing thermal comfort, failure in predicting the ~~non-~~nonstationary thermal characteristics of a moving person, and underestimation of Tmrt at low solar angles

As another bioclimatic ~~modelling~~modeling system, ~~Townscope~~ TownScope is used for geometrical analysis of a 3D urban environment. The bases of calculations in this model include mean daily average air temperature, wind speed, humidity, and surface temperature [25]. However, researchers using this model cannot alter the meteorological and weather files in the calculation. The vegetation package of the system is also extremely sophisticated. The main limitations of TownScope ~~is~~ are that it keeps the meteorological parameters constant during simulation and simplifies the vegetation scheme.

~~Table 2 lists the main limitations of the studied bioclimatic modelling systems.~~

~~Table 2. Limitations of different bio-climatic modelling systems [27].~~

~~Bio-climatic modelling system~~	~~Limitations~~
~~RayMan~~	~~Uses limited thermal indices in assessing thermal comfort, cannot predict non-stationary thermal characteristics of a moving person and underestimates Tmrt at low solar angles~~
~~SOLWEIG~~	~~Uses limited thermal indices in assessing thermal comfort, simplifies the vegetation scheme, calculates radiative fluxes from all directions and neglects some climatic parameters affecting comfort~~
~~Fluent~~	~~Long computation time~~
~~TownScope~~	~~Keeps meteorological parameters constant during simulation and simplifies the vegetation scheme~~

ENVI-met, a complete bioclimatic tool

This study selects ENVI-met (3.1 beta 5) [3], which is a 3D microclimatic ~~modelling~~modeling system, to achieve the research objectives. ENVI-met is one of the most sophisticated models among all urban ~~micro~~

~~climate~~ microclimate models~~,~~ and it includes all energy and radiative processes in ~~the~~ urban environments [34]. ENVI-met is used to simulate the interaction among surfaces, plants, and air in an urban environment and ~~employs~~ uses a typical resolution of 0.5 m to 10 m in space and 10 s in time. Simulations are generally performed for at least 24 h; however, the accuracy of results can be improved by running the simulations for 48 h [35].

In this study, ENVI-met is used for ~~modelling~~modeling because it can simultaneously calculate meteorological parameters, surface energy fluxes, and soil and vegetative processes within a complex urban environment by using a diverse range of urban configurations [7, 36]~~.~~.

In predicting outdoor thermal comfort level, ENVI-met uses Tmrt, air temperature, relative humidity, and wind velocity as inputs. This tool provides the most accurate value in predicting thermal indices.

ENVI-met is preferred for calculating outdoor thermal comfort because this ~~bio-climatic modelling~~ bioclimatic modeling system can simulate microclimate dynamics on a daily basis. The model also predicts all radiation exchange processes, such as wind flow, turbulence, radiation flux, temperature, and humidity. ENVI-met possesses a comprehensive set of vegetation schemes and can model an urban setting in diverse contexts. This model does not consider vegetation ~~as~~ a porous obstacle to wind and solar irradiance and includes the physiological processes of evapotranspiration and photosynthesis in ~~the~~ calculations.

In ENVI-met, soil consists of different layers. Using high spatial (up to 0.5 m horizontally) and ~~high~~ temporal ~~resolution~~ (up to 10 s) resolutions provides a detailed illustration of microclimatic changes, especially alterations in parameters that affect comfort and urban geometry. Initiating the model with numerous outputs requires few inputs. Moreover, ENVI-met can calculate Tmrt, which is the most important parameter in determining thermal comfort.

ENVI-met has been widely applied to several studies worldwide to investigate the influences of greening [7, 37-46] and design-related parameters on microclimate [7, 42, 47, 48]. However, this tool may not provide accurate values for the required outputs. ~~Nevertheless, all modelling~~All modeling systems must be validated against field measurements to determine their capability to produce accurate outputs within ~~the~~ an urban environment. This step is usually ignored by planning professionals because of complexities and difficulties in measuring individual variables in urban areas [49]. Several studies have established few helpful tools for comparing different scenarios [50]. Scholars have performed minor or major modifications on the input or boundary area setting to reduce the discrepancy between the simulated and measured outputs.

The following section provides a thorough review of previous validation studies. Field measurements are conducted to examine the reliability of ENVI-met in answering research questions. Table ~~3~~ 1 presents a comparison of various ~~modelling~~modeling systems according to the required criteria in addressing the research questions.

Table ~~3~~ 1. Comparison of various ~~modelling~~modeling systems.

Criteria	1D model	2D model	CTTC	RayMan	SOLWEIG	Fluent	TownScope	ENVI-met 3.1
Computation time	✓	✓	✓	✓	✓	×	✓	×
Considering urban geometry	×	✓	✓	✓	✓	✓	✓	✓
Predefined assumptions	✓	✓	✓	×	×	×	×	×
Including vegetation scheme	✓	✓	✓	×	×	✓	✓	✓
Forcing meteorological parameters	×	×	×	✓	×	×	×	×
Limited thermal indices	✓	✓	✓	✓	×	✓	✓	×
Spatial resolution	×	×	×	×	×	✓	×	✓
Limited inputs to generate meaningful outcomes	×	×	×	×	×	×	✓	✓
Calculation of Tmrt	×	×	×	✓	✓	✓	✓	✓

~~How accurate~~ Accuracy of ENVI-met ~~is~~ (~~review~~ Review of previous studies)

Validation with field measurement is an integral part of simulation-based studies. ~~To demonstrate the accuracy of ENVI-met, this~~ This section provides a comprehensive review of previous studies that have used ENVI-met as the main tool to demonstrate its accuracy. The methods and validation conducted in each study are also discussed.

A study conducted in Glasgow, ~~United Kingdom~~UK used ENVI-met to evaluate the efficiency of various green infrastructures in addressing the overheating problem in cold-climate urban agglomeration. This validation study revealed that air temperature is overestimated during ~~night~~ nighttime and underestimated during daytime [51]. A similar study conducted in Beijing, China evaluated the influence of landscape on microclimate variation and achieved a reasonable agreement between ~~the~~ measured and simulated outputs (coefficient factor of 0.8087) [52]. However, a similar study conducted in Manchester, UK obtained a low coefficient factor (R^2 = 0.56) and attributed the difference between ~~the~~ field data and simulated outputs to the elimination of various building envelopes, U values, and internal air temperature for each building [53]. Air temperature, relative humidity, wind velocity, and solar irradiance were validated at 12 points in Japan to examine the effect of greening on

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reducing the ambient air temperature at the pedestrian level. A cloudless sky was selected as the weather condition for a simulation day, and the spatial and temporal ~~variability~~ variabilities ~~of~~in the sky condition in the field measurement ~~was~~were ignored, thereby resulting in overestimation of solar irradiance [54]. A similar result was obtained in a study conducted in Damascus, Syria under a different climatic condition. ENVI-met slightly overestimated the solar radiation for the study areas (solar radiation was reduced to 85%). Some deviations were also observed between ~~the~~ simulated and field data results. Therefore, ~~the~~ input values, including initial atmospheric temperature, soil, wind speed 10 m above ground, and specific and relative humidity, were adjusted [55]. In a study in Hong Kong, ENVI-met showed a reasonable agreement between ~~the~~ measured and simulated data for air temperature (R^2 = 0.745) and Tmrt (R^2 = 0.615) [56]. However, a similar study conducted in Manchester, UK observed a large temperature difference between ~~the~~ measured and simulated temperatures in ~~some~~ several receptors. The authors concluded that at least three nesting grids and five empty grids were required for a large ~~modelling~~modeling domain. Soil humidity~~,~~ and upper ~~temperature,~~ and middle temperatures were changed ~~according to~~ on the basis of a previous study conducted in this area. The model version used in this study was limited to starting temperature and wind condition as factors; therefore, the values could not be forced during the simulation [53].

Several studies validated the use of ENVI-met to determine the effect of urban shading on microclimate and outdoor thermal comfort. For instance, a study in Malaysia used ENVI-met to examine the thermal performance of an unshaded courtyard and reported agreement between ~~the modelled~~modeled and real data of meteorological parameters [57]. ENVI-met was also used to evaluate the influence of adding shading trees to ~~the~~a street canyon on the ~~sub-~~subtropical climate of ~~Sao~~ São Paulo, Brazil; in this work, the tool overestimated solar radiation~~,~~ ~~which~~ decreased to 90%. The application of the same material for all buildings and the absence of heat storage in the building properties could cause a discrepancy between ~~the~~ measured and simulated values. The coefficient factor between the measured and simulated values (based on 79 values) increased to 0.7487 after minor modifications [58].

ENVI-met was also validated in studies that assessed the ~~effect~~effects of urban design strategies, built form, street structure, and urban form on meteorological parameters. ENVI-met was used to assess thermal comfort in different urban tissues in São Paulo, Brazil. The model underestimated the values for air temperature because the regional climatic condition was eliminated [59]. A similar study examined the effects of urban design strategies on pedestrian thermal comfort. The simulated outputs of the model did not perfectly match ~~the~~ field data. Therefore, the model was identified as a suitable tool for comparison-based studies only. The discrepancy between ~~the~~ measured and simulated values could be attributed to the ~~non-~~ nonnested model boundary, constant values of potential temperature and humidity at 2,500 m height during ~~the~~ simulation without external forcing for ~~the~~ meteorological data, ~~as well as~~ and the lack of thermal mass in building properties [60].

In the Netherlands, ~~the~~ measured and simulated air temperatures presented similar patterns on the first day of measurement. ~~However, on~~ On the second day, the number and time of the hottest hours showed ~~some~~ inconsistencies. The study conducted necessary adjustments in the model and reported that the final correlation coefficient between the two sets of data increased to 0.80 [61]. Wang and Akbari found that ENVI-met underestimated the air temperature and overestimated the relative humidity in Montreal, Canada during daytime and ~~night-~~nighttime. The difference between ~~the~~ measured and simulated outputs could be due to the following: (1) unified and assumed numerical values of ~~the~~ material properties for simulation, (2) disregarding actual cloud coverage in the model and the influence of horizontal long-wave ~~fluxes~~ fluxes, and (3) large time intervals (10 min) for updating the sun position and the radiative ~~fluxes~~ fluxes from the sky [62]. Scholars in Malaysia assessed the ~~effect~~effects of trees and ground material modification on reaching the maximum cooling effect and mitigating the heat island effect. ENVI-met underestimated the average values of ~~the~~ air and surface temperatures. The initial temperature was increased by 2 °C to improve the correlation between ~~the~~ measured and simulated values. The average wind speed was altered from 2.1 m/s to 1.1 m/s because of strong variation in the measured wind speed in terms of direction and speed during daytime [63]. Hamza and Dudek conducted a validation study on climatic conditions in Cairo, Egypt and found that the model underestimated the Tmrt values after sunset; the results could be due to the reduced short-wave radiation after sunset. The lack of heat storage in building properties resulted in daytime overestimation and ~~night-~~nighttime underestimation of long-wave radiation emitted by walls. After several modifications, the coefficient values for air temperature and Tmrt increased to 0.942 and 0.916, respectively [64].

Few studies validated wind ~~behaviour~~behavior by using ENVI-met. Krugler conducted a validation study on ENVI-met in Curitiba, Brazil and reported that the measured and simulated values for wind speed below 2 m/s were consistent ($R^2 = 0.80$). However, ENVI-met often overestimated the wind speed within a canyon for input wind speeds over 2 m/s ($R^2 = 0.70$) [65].

The discrepancy between ~~the~~ measured and simulated values is not always due to the ~~modelling~~modeling incapability of ENVI-met. Different methodological approaches may also result in differences in numerical values. For instance, ENVI-met that ~~used~~ uses reference ~~weather station~~ data from weather stations is ~~not~~ an inappropriate representative of ~~the~~a study site.

ENVI-met version 4.0 was used to investigate the ~~effect~~effects of different orientations and canyon aspect ratios on street-level microclimate in Rajarhat Newtown, India. ENVI-met ~~presents~~ presented certain limitations in ~~modelling~~modeling microclimate in terms of limited domain size (100 m × 100 m grid), exclusion of single walls as a design element, and exclusion of the effect of sea breeze on ~~the~~ wind speed [66].

A study used ENVI-met 3.1 to quantify the optimum cooling effect of trees with modified ground materials in the tropical climate of Putrajaya. A strong correlation was found between ~~the~~ measured and ~~modelled~~modeled values~~, confirming~~ and confirmed the reliability of ENVI-met in predicting existing air and ground surface temperatures [63].

A similar study assessed the capability of unshaded courtyards in cooling outdoor spaces by using different design configurations and scenarios (e.g., orientation, height and albedo of wall enclosure, and vegetation). The predicted values and real data of meteorological stations showed acceptable agreement after minor adjustments were implemented [57]. Scholars developed a recent version of ENVI-met, namely, ENVI-met V4 Beta software, to evaluate the thermal performance of different hot spots in an urban complex. The model showed ~~(R2)~~R^2 of 0.69 < 1, ~~indicating~~ which indicated a statistically significant correlation. Moreover, the model had a Nash–Sutcliffe coefficient of efficiency (E) of 0.91 and index of agreement (d) of 0.91, which ~~are~~were close to 1, ~~thereby indicating~~ which indicated perfect performance [67]. Yang [68] reviewed studies that assessed ENVI-met and observed the improved performance of the new version of ENVI-met V~~.~~4 in terms of root mean square error (RMSE) values and index of agreement (d) compared with the previous version (V~~.~~ 3.1) for air temperature evaluation. Table ~~4~~ 2 presents the objective of validation studies that used ENVI-met as primary software, the limitations of the model, and the validation outcomes.

Table ~~4~~2~~.~~ Results of previous validation studies that used ENVI-met.

Purpose of investigation	Limitation of ENVI-met	Validated ENVI-met	Reference	Location
To assess the efficiency of green infrastructure in addressing the potential overheating problem in cold-climate urban agglomerations	ENVI-met overestimated and underestimated the air temperature values during ~~night~~ nighttime and daytime, respectively.	Modifications were needed.	[19]	Glasgow, UK
To investigate the thermal performance characteristics of unshaded courtyards in hot and humid climates	ENVI-met exhibited a high level of agreement between ~~the~~ recorded and ~~modelled~~modeled meteorological values.	Modifications were needed.	[69]	Malaysia

To assess thermal comfort in different urban tissues	ENVI-met underestimated the values of air temperature by disregarding the regional climate effects.	Modifications were needed.	[83]	São Paulo, Brazil
To measure the effect of landscape on microclimate variation	ENVI-met achieved a reasonable agreement between the simulated and field data on air temperature with a coefficient factor of 0.8087.	Yes	[357]	Beijing, China
To assess the cooling effects of trees and cool roofs on a residential ~~neighbourhood~~neighborhood	ENVI-met showed RMSEs of 1.41 °C (mesic), 1.81 °C (oasis), and 2.00 °C (xeric) for air temperature at 2 m above the ground level.	Yes	[367]	Phoenix, ~~United States~~US
To assess the effects of various building geometries in four typical urban districts on outdoor temperature and comfort	ENVI-met underestimated the air temperature and overestimated the relative humidity for daytime and ~~night~~ nighttime. The numerical values of the material properties for the simulation were unified and assumed. The actual cloud coverage was ignored in the model, the effect of horizontal long-wave ~~fluxes~~fluxes was ignored, and large time steps (10 min) were used to update the sun position and radiative ~~fluxes~~ fluxes from the sky. After adjustments, the coefficient values for air temperature and relative humidity reached 0.78 and 0.7, respectively.	Modifications were needed.	[368]	Montreal, Canada
To investigate the effect of adding shading trees on ~~the~~a street canyon	ENVI-met overestimated the solar radiation for the São Paulo condition. Therefore, solar radiation was reduced to 90%. This discrepancy was attributed to the application of the same material for all buildings and the absence of heat storage in building properties. After minor modifications, the coefficient factor between ~~the~~ measured and simulated values (based on 79 values) was improved to 0.7487.	Modifications were needed.	[275]	São Paulo, Brazil
To evaluate the ~~effect~~effects of trees and ground material modification on maximizing the cooling effect and mitigating the heat island effect	ENVI-met underestimated the average values of air and surface temperatures. Therefore, the initial temperature was increased by 2 °C to achieve improved correlation between ~~the~~ measured and simulated values. The average wind speed changed from 2.1 m/s to 1.1 m/s because the measured wind speed and direction varied strongly during the day.	Modifications were needed.	[364]	Malaysia
To simulate outdoor air temperature, ~~mean radiant temperature~~Tmrt, wind speed, and relative humidity	The variations in ~~the~~ measured and ~~modelled~~modeled air temperatures were similar, and their final correlation coefficient was 0.80 after the adjustment.	Modifications were needed.	[362]	The Netherlands
To evaluate the microclimate of an outdoor urban form	ENVI-met underestimated Tmrt after sunset hours because of the reduced short-wave radiation after sunset. The lack of heat storage in ~~the~~ building properties in ENVI-met led to daytime overestimation and ~~night~~ nighttime underestimation of long-wave radiation emitted by walls. After the modifications, the coefficient values for air temperature and Tmrt reached 0.942 and 0.916, respectively.	Modifications were needed.	[365]	Cairo, Egypt
To evaluate the ~~effect~~effects of various greening scenarios on microclimate on the block and ~~neighbourhood~~neighborhood scales	The regression analysis between ~~the~~ measured and simulated air temperatures did not show a reasonable agreement (R^2 = 0.56). The model did not allow for variations in building envelope, U values, or internal temperatures for individual buildings. The model also did not allow forcing of weather variables. The model had a long running time.	Modifications were needed.	[358]	Manchester, ~~United Kingdom~~UK

To assess the effect of greening on lowering the ambient air temperature at the pedestrian level	Air temperature, relative humidity, wind velocity, and solar irradiance were validated at 12 points by using on-site measurements. ENVI-met overestimated solar irradiance. ~~The spatial~~ Spatial and temporal differences were not recorded during the field measurement. Therefore, a cloudless sky was selected as the weather condition for a simulation day, ~~leading~~ which led to the deviation between ~~the~~ measured and simulated solar values.	Modifications were needed.	[369]	Japan
To evaluate the ~~effecte~~effects of landscape elements on thermal comfort for detached buildings	ENVI-met tended to slightly overestimate the solar radiation in the study area, ~~thereby reducing~~ which reduced the solar radiation to 85%. Some deviations were also recorded between ~~the~~ simulated and field data. Therefore, ~~the~~ input values, including initial atmospheric temperature, soil, wind speed at 10 m above ground level, and specific and relative humidity, were adjusted.	Modifications were needed.	[370]	Damascus, Syria
To simulate near-ground air temperature in a typical residential ~~neighbourhood~~neighborhood	ENVI-met achieved a reasonable agreement between the simulated and field data for air temperature 2 m above ground.	Yes	[21]	Phoenix, US
To evaluate the effect of downtown greening on microclimatic data	ENVI-met achieved a reasonable agreement between the measured and simulated data for air temperature ($R^2 = 0.745$) and Tmrt ($R^2 = 0.615$).	Yes	[371]	Hong Kong
To investigate the ~~effecte~~effects of urban design strategies on pedestrian thermal comfort	The discrepancy between ~~the~~ measured and simulated values could be attributed to the ~~non-~~nonnested model boundary, the constant values of the potential temperature and humidity at 2,500 m above ground during the simulation without external forcing for the meteorological data, ~~as well as~~ and the lack of thermal mass in ~~the~~ building properties.	Modifications were needed.	[274]	Shanghai, China
To assess the effect of vegetation on temperature reduction during extreme heat events	The simulation depended on validating air temperature by collecting data from Phoenix, ~~United States~~US, with vegetation and microclimatic conditions similar to those in the study area.	Yes	[288]	Phoenix, US
To evaluate the ~~effecte~~effects of seven greenspace scenarios on microclimate	~~In some receptors, a~~A large temperature difference was observed between the measured and simulated temperatures in several receptors. ~~According to the~~ The ENVI-met documentation~~,~~ indicated that at least three nesting grids and five empty grids were required for a large ~~modelling~~modeling domain. Soil humidity~~,~~ and upper ~~temperature,~~ and middle temperatures were changed according to a previous study [62]. ~~Given that the model version used in this study was limited to starting temperature and wind condition, the~~ The values could not be forced during the simulation, given that the model version used in this study was limited to starting temperature and wind condition.	Modifications were needed.	[358]	Manchester, UK
To assess the effect of street orientation on prevailing winds and its consequences on ventilation and wind speed at the pedestrian level	The measured and simulated values were consistent ($R^2 = 0.80$) for wind speeds below 2 m/s. However, ENVI-met overestimated the wind speed within ~~the~~a canyon for input wind speeds over 2 m/s ($R^2 = 0.70$).	Modifications were needed.	[366]	Curitiba, Brazil
To explore the ~~effects~~ effect of architectural design on thermal performance in outdoor environments	An insignificant difference was observed between air temperature and wind speed across canyons because of limited thermal heat storage in buildings.	Modifications were needed.	[39]	Algeria

Methodology

In this section, one of the fastest growing suburbs in Melbourne ~~which~~ that ~~is~~will be the subject of rapid urban development in the future is studied. One of the visions of Melbourne City Council for future urban developments is to quantify the thermal and climatic consequences of implementing the proposed urban growth scenarios. Therefore, this section ~~of the paper~~ explains the validation process for the model ~~which~~ that ~~is going to~~ will be used as the base for future urban growth scenarios and assess the reliability of ENVI-met in accurately ~~modelling~~modeling ~~the~~ simulated outputs.

The methodology section ~~has been~~ is divided into two parts~~:~~. In the first section, ~~in the first section the~~ ~~The~~description of the ~~,~~study area, selection of ~~the~~ measurement points and their physical characteristics, process of field measurements, equipment~~'s~~ used to conduct ~~the~~ field measurements, and ~~the~~ monitored values are explained~~ in the first part~~. The second part ~~of the methodology~~ discusses the simulation approach, ~~setting up~~ the establishment of the model with accurate inputs and configuration parameters, and ~~compares~~ the comparison of the results of the simulated and measured values through RMSE calculation. Finally, the validation process of the model and the adjustments needed for the control parameters are ~~discussed~~described.

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Study area and field measurements

City North (Carlton), Melbourne, which is subject to future urban renewal and development, was selected as the study area. Seven points with diverse design features were selected to begin the field measurements. The selected points included two sites with varying street widths and a similar orientation, two urban sites with different street orientations and a similar H/W ratio, two urban canyons under a tree canopy (one was located in an urban park and the other under a tree canopy on a street), and a reference control site in an open space area. Each site was positioned in predominantly mixed-use (residential–commercial) areas that are subject to future urban development. Figure 1 shows the location and position of each measurement point in the site. ~~The climatic~~ Climatic parameters were measured in the middle part of each canyon. For certain points, the installation of HOBO data loggers was ~~not~~ infeasible due to safety and security reasons. However, none of the HOBO data loggers were obstructed or shaded by trees and other buildings.

Figure 1. Location of selected points for on-site measurement (Source: [69]).

~~Source: [69]~~

Measurement was conducted for peak warm weather in Melbourne. Field measurements were performed in January because this month has the hottest days throughout the year and the air temperature~~r. Table 5 shows that the air temperature in January~~ can ~~reach~~ reach ~~to~~ 38.8 °C. Although the climate data from the Melbourne Olympic Park in January 2015 identified January 2 and 3 as two of the hottest days of the month, field measurement was conducted on these days due to the lower wind speeds in January 5 and 6. ~~(the~~ The purpose was to conduct ~~modelling~~modeling and simulation when warmer urban temperatures are more likely to induce human thermal stress, and climate is associated with high air temperature and low wind speed~~)~~. Figure 2 illustrates the air temperature variation recorded at the Melbourne Olympic Park weather station in January 2015.

~~Table 5. Highest monthly air temperature from 1961 to 1990, Source: [71].~~

~~Statistic~~	~~Jan~~	~~Feb~~	~~Mar~~	~~Apr~~	~~May~~	~~Jun~~	~~July~~	~~Aug~~	~~Sep~~	~~Oct~~	~~Nov~~	~~Dec~~

~~Average highest temperature (°C)~~	~~38.8~~	~~36.1~~	~~32.9~~	~~29~~	~~23.1~~	~~18.3~~	~~17~~	~~18.8~~	~~24.3~~	~~31.6~~	~~32.7~~	~~33.1~~

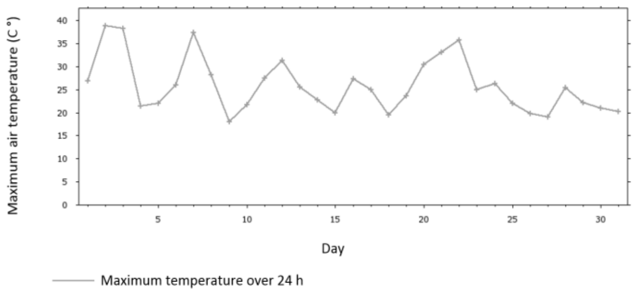


Figure 2. Maximum recorded air temperatures at Melbourne Olympic Park (Station number: 086338) in January 2015~~,~~ (Source: [70]).

From January 5, 2015 at 7:00 to January 6, 2015 at 19:00, on-site~~ field~~ field measurements were conducted under sunny and clear skies. A portable weather station was installed 3 m above the ground. ~~At selected points in the study area, four~~ Four HOBO onset data loggers (2 m above the ground) and two comfort carts were installed at selected points in the study area to record air temperature. A Nikon Coolpix 5400 camera with a fisheye converter and a 180° angle of view was used to capture sky-view factor images at the measurement points. Measurements were ~~taken using~~ collected from ~~the~~a weather station, comfort carts, and HOBO onset data loggers at 1 h, 15 min, and 5 min intervals, respectively. The simulated hourly outputs were validated by converting all the recorded climatic variables into hourly data.

~~The first site (point~~ Point 1~~)~~ was an open area with asphalt pavement and had almost no obstruction to the sky. This point was operated as a regional weather station for the field measurement. ~~The second point~~ Point 2 was located under a dense tree canopy with 20 m height and a distinct crown layer at the University Square Park. This point was covered with a grass surface and had ~~less~~minimal exposure to the sky because of the shading by the surrounding trees. Point 3 was located in the middle of an east–west-oriented canyon with asphalt pavement. This site was surrounded by medium-height (two to three stories) residential units and a few recently built high-rise buildings. Point 4 was located in the middle of the ~~northwest~~NW–~~southeast~~SE-oriented boulevard with vegetated areas in the middle of the canyon. The data logger at this point was installed on a pole in the middle of the boulevard on top of the planted area. This point was not shaded by any tree. The surface was covered by grass, and the canyon was wider than that in all other sites. This site comprised buildings with varying heights of 2 to 12 stories. Point 5 was located in an asphalt-paved urban canyon with an orientation similar to that of

~~point~~ Point 4. However, the street canyon at ~~point~~ Point 5 was narrower than that at ~~point~~ Point 4. Similar to ~~point~~ Point 4, ~~the building height~~ at ~~point~~ Point 5, building heights ranged from 2 to 12 stories. As a result, ~~point~~ Point 5 had a higher H/W ratio than ~~point~~ Point 4. Point 6 was located in an asphalt-paved canyon perpendicular to the canyon at ~~point~~ Point 3. The width of streets at ~~points~~ Points 3 and 6 was almost equal~~,~~; ~~but~~ however, the taller buildings at ~~point~~ Point 6 resulted in a higher H/W ratio at this point. A construction site and an urban park were located on both sides of the street at ~~point~~ Point 6. Point 7 was located under a 20 m~~-~~-high average dense tree canopy on Victoria Street. The surface was covered with grass, and the building height varied from 2 to 24 stories.

These points were selected to cover various urban canyons with different features, such as H/W ratio, surface material, proximity to vegetated areas, and SVF. For instance, ~~points~~ Points 4 and 5 were situated in urban canyons with the same orientation (NW–SE) but had different street widths and H/W ratios. Points 3 and 6 were located in street canyons with almost equal H/W ratio but different orientations (perpendicular to each other). Points 1 and 7 were located below the canopy of dense trees, with the former located in an urban park and the latter located on Victoria Street. Table ~~6.2~~3 shows the detailed characteristics of the selected measurement points. Table ~~6.3~~4 presents the images of the selected canyons and corresponding SVF images.

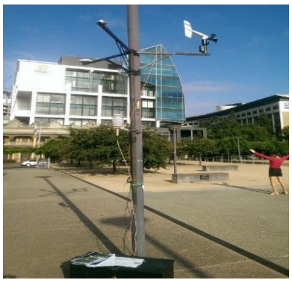
Table ~~6~~3. Characteristics of selected points for on-site measurement [71].

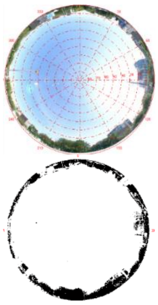
Point	Site characteristic	SVF value	Surface type	H/W ratio	Height of measurement	Equipment used	Symbol
1	Open space	0.9	Asphalt	_	3 m	Portable weather station	
2	Under a tree canopy in a park	0.2	Grass	_	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	
3	E–W-oriented street canyon	0.5	Asphalt	0.5	2 m	HOBO data logger	
4	NW–SE-oriented street canyon	0.8	Grass	0.8	2 m	HOBO data logger	
5	NW–SE-oriented street canyon	0.4	Asphalt	2.7	2 m	HOBO data logger	
6	N–S-oriented street canyon	0.6	Asphalt	0.4	2 m	HOBO data logger	
7	Under a tree canopy in a street	0.3	Grass	1.4	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	

Table ~~7~~ 4. Selected canyons and SVF images of measurement points.

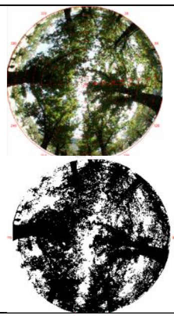
Point	Selected canyon	SVF image

Point 1

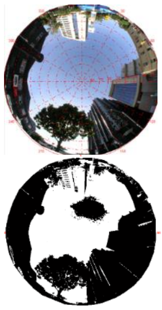




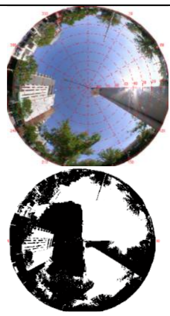
Point 2



Point 3



Point 4



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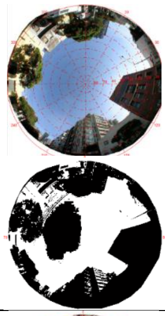
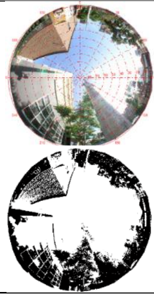
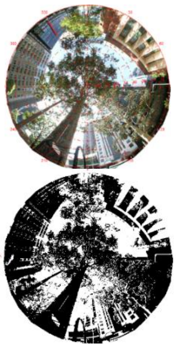
Point 5		
Point 6		
Point 7		

Equipment used for on-site measurement

Comfort carts, HOBO data loggers, a portable weather station, and a fisheye camera were used to capture SVF images. The comfort study recommended the measurements to be taken at 1.1 m. However, the HOBO data loggers and weather station were installed at 2 m and 3 m above the ground level, respectively, to avoid sensor damage in the study area. According to a study conducted by Oke, the measurement equipment should be installed at the standard observational height, which could vary from 1.25 m to 2 m. Oke also observed ~~very slight~~ minimal gradients for air temperature measured throughout the urban canopy layer [72].

The accuracy ranges of the ~~employed~~ used equipment complied with ISO 7726 recommendations. ~~Table 8 lists the measured variables, sensor height, and logging interval for each instrument. Table 9 presents the level of accuracy of the portable weather station in measuring various climatic parameters.~~

~~Equipment~~	~~Parameter~~	~~Sensor height~~	~~Logging interval~~
~~HOBO H08-003-02~~	~~Air temperature and relative humidity~~	~~2 m~~	~~15 min~~
~~Portable weather station~~	~~Air temperature, relative humidity, wind speed and direction, global solar radiation, global illuminance precipitation and air pressure~~	~~3 m~~	~~15 min~~
~~Comfort cart~~	~~Air temperature, globe temperature, relative humidity, wind speed and direction, PMV and CO_2~~	~~Four different heights (0.1, 0.6, 1.1 and 1.7)~~	~~15 min~~
~~Nikon Fisheye Converter FC-E9 0.2x~~	~~SVF images at different points~~		

~~Table 8 Descriptions of equipment used in the study area.~~

~~Table 9 Accuracy level in measuring different climatic variables by portable weather station.~~

~~Variables~~	~~Accuracy~~
~~Air temperature~~	~~±0.7 °C (0–40 °C)~~
~~Relative humidity~~	~~±5% (5–50 °C)~~
~~Wind speed~~	~~±3%~~
~~Solar radiation~~	~~1.5% +5 W/m2~~
~~Globe temperature~~	~~±0.25 °C (0–50 °C)~~

HOBO data loggers were used at ~~points~~ Points 3~~, 4, 5 and to~~–6, and a ~~fixed~~ fixed meteorological monitoring station was installed at ~~point~~ Point 1 as reference. Various climatic parameters were recorded using different sensors in the station. Wind monitors, temperature and humidity sensors, and global illuminance and solar radiation sensors were installed in the weather station. Simulation was ~~initialised~~initialized using the recorded air temperature, relative humidity, wind speed, ~~–~~and wind direction at ~~point~~ Point 1 as the initial climatic variables.

A comfort car was used in the measurement. This tool was designed to assess thermal environments inside buildings according to procedures and protocols in the thermal comfort standard of ASHRAE [73]. The environment was measured by each cart simultaneously at four heights within the occupied zone. These heights are coded with the following ~~colours~~colors:

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• [Black] HEAD (1.7 m above floor level corresponds to the head of a standing person) (a)

• [Red] HI (1.1 m above floor level corresponds to the head of a seated person) (b)

• [Blue] MID (0.6 m above floor level corresponds to the waist of a seated person) (c)

• [Green] LO (0.1 m above floor level corresponds to the ankles of a seated person) (d)

Figure 3 presents a comfort cart installed at ~~point~~ Point 2 under the canopy of a tree in an urban park at the University Square. Figure 3 shows four different heights of measurement in the comfort cart. Figure 4 ~~shows~~depicts the second comfort cart installed under the tree canopy on Victoria Street (~~point~~ Point 7). ~~Table 10 presents the accuracy level and technical details of the comfort carts used in this study.~~

Figure 3. Comfort cart at ~~point~~ Point 2 under ~~a~~the shade of a tree canopy in an urban park (University Square).

Figure 4. Comfort cart at ~~point~~ Point 7 under ~~a~~the shade of a tree canopy on Victoria Street.

~~Table 10. Technical details and accuracy level of comfort carts used in this study.~~

~~Sensor~~	~~Specification~~
~~Three x TSI omnidirectional anemometers (model number 8475)~~	~~- Time constant adjustable from 0.2 to 2 s, with default time set to 0.2 s.~~ ~~- Range = 0.05–2.5 m/s~~ ~~- Accuracy = 3% of reading (e.g. < 0.01 m/s for typical indoor environments)~~
~~Three x OMEGA 44032 linear thermistor composites for air temperatures~~	~~- Interchangeability = 0.1 °C~~ ~~- Time constant = 1 s~~
~~Three x OMEGA 44032 linear thermistor composites for globe temperatures~~	~~- Interchangeability = 0.1 °C~~ ~~- Time constant = approximately 10 min~~

~~One HyCal integrated circuit humidity sensor (IH-3605-B)~~	~~- Repeatability = 0.5% RH at 25 °C~~ ~~- Total accuracy = 2% RH at 25 °C~~ ~~- Hysteresis = 0.8% of span max~~ ~~- Time constant = 15 s at 25 °C~~

Hemispherical digital images were taken with a fisheye lens camera from the ~~centre~~center of each urban canyon, and the SVF value at each selected point in the urban canyons was calculated. Figure 5 shows that SOLWEIG 1D was used to convert the SVF images into their corresponding SVF values at each point. ~~Table 11 lists the features of the digital camera used to take the images.~~

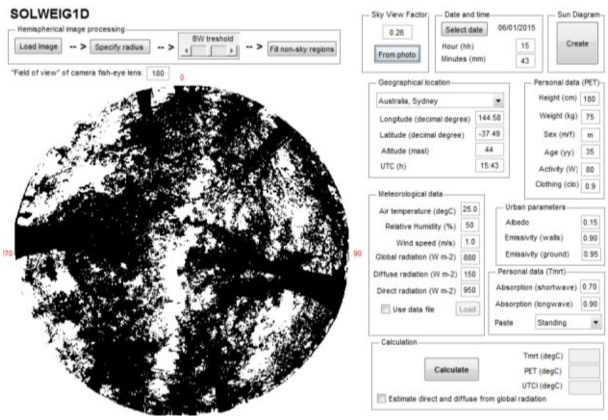

Figure 5. Calculating SVF value from fisheye camera images in SOLWEIG 1D.

~~Table 11. Technical details of fisheye camera for taking SVF photos.~~

~~Nikon Coolpix 5400~~
~~Lens: Nikon Fisheye Converter FC-E9 0.2x~~
~~Angle of view: 180°~~

Results of ~~onsite~~on-site measurement

The climatic data ~~reveal~~ show fluctuations in ~~the~~ air temperature, relative humidity, and wind speed in the study area during the measurement dates. This variation is observed not only at different times of the measurement but also at different measurement points. The difference in the average recorded climatic data at different measurement points can be attributed to the accuracy of the equipment, the location of the equipment during the measurement, the proximity to construction sites, and the geometry of each canyon.

The mean daytime air temperature varies from 24 °C to 29.6 °C across the seven measurement points. This fluctuation is significantly lower under the ~~night~~ nighttime condition, during which the maximum difference in the monitored data is only 0.6 °C. Similar to daytime and ~~night~~ nighttime air temperature patterns, the relative humidity during the day shows a higher level of fluctuation than that during the night. The mean daytime relative humidity ranges from 45% to 58%, and the ~~night ~~nighttime relative humidity varies from 83% to 87%. Wind speed has the lowest level of variation; only a 1.7 m/s difference is observed between the highest and lowest wind speed values at different measurement points. Table ~~12 ~~5 lists the maximum and minimum measured ~~air temperature, relative humidity and wind speed ~~air temperatures, relative humidities, and wind speeds during the measurement. Figure 6 shows the variations in air temperature at different measurement points. Figure 7 presents the variations in relative humidity at different measurement points. Figure 8 shows the variations in wind speed.

Table ~~12~~5. Differences in measured data at various measurement points during daytime and ~~night ~~nighttime.

Climatic parameter	Min		Max		(Max~~–~~–Min)	
	Day	Night	Day	Night	Day	Night
Air temperature (°C)	24.5	19.8	29.6	20.5	5.1	0.7
Relative humidity (%)	45	83.3	58	87.2	13	3.9
Wind speed (m/s)	0.3		2		1.7	

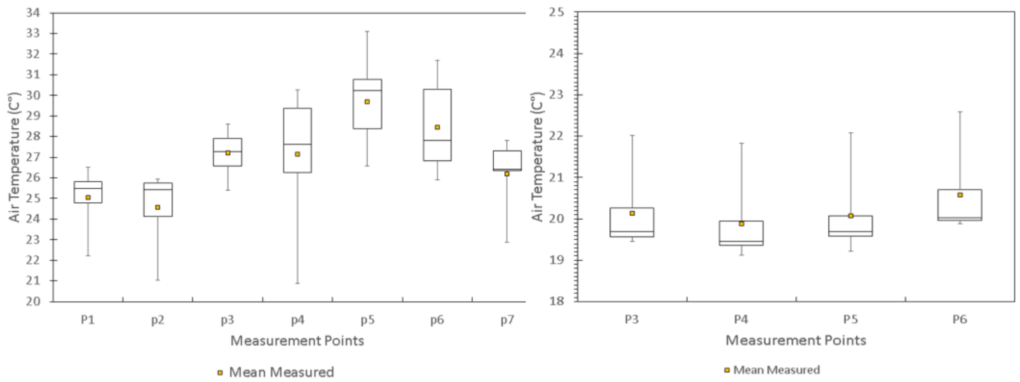

Figure 6. Monitored air temperature at selected measurement points during daytime (9:00–17:00~~)~~; ~~(~~left) and ~~night ~~nighttime (22:00–5:00~~)~~; ~~(~~right).

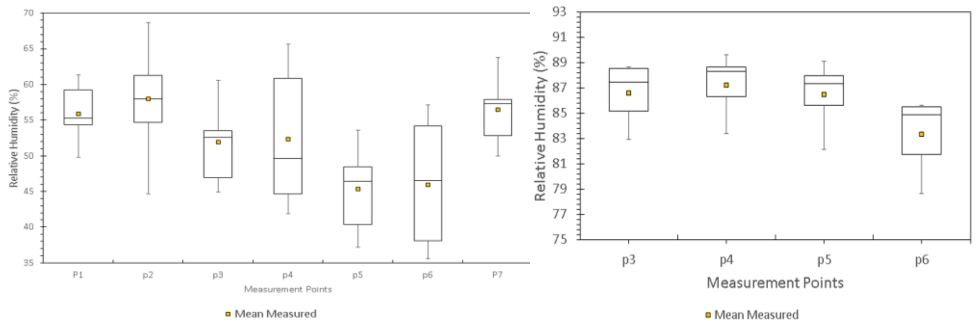

Figure 7. Monitored relative humidity at selected measurement points during daytime (9:00–17:00~~)~~; ~~(~~left) and ~~night~~ nighttime (22:00–5:00~~)~~; ~~(~~right).

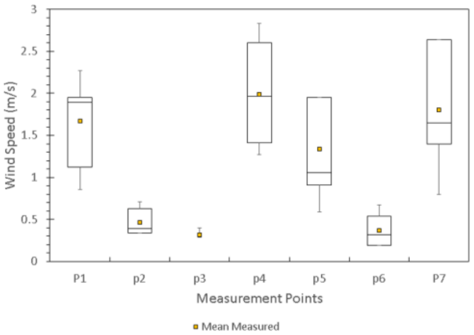

Figure 8. Monitored wind speed at daytime (9:00–17:00).

Simulation approach and verification against field measurements

The model of the study area was ~~set up~~ constructed using the area input file (Table ~~13~~6) and configuration file (Table ~~14~~7). The configuration file was used as starting point to run the initial ENVI-met model as closely as possible to the observed air temperature determined at each measurement point.

Table ~~13~~ 6. Initial ~~set up~~setup of the model domain (area input file) [71].

Input setup	Value
Orientation (degree from the north)	7
Number of x grids	230
Number of y grids	230
Number of z grids	30
Size of grid cell in m (dx)	3
Size of grid cell in m (dy)	3
Size of grid cell in m (dz)	2
Name of location	Melbourne, Australia
Position on ~~earth~~the Earth	Latitude (−37.49), longitude (144.58)
Number of nesting grids	5
Soil profile for nesting grids	Soils A and B = Loamy soil

Table ~~14~~ 7. Settings for the configuration file used to run the initial ENVI-met model [71].

Input for configuration file	Value
Start simulation	1:00, January 6, 2015
Total simulation time in hours	48 h
Save model state (each min)	60
Wind speed at 10 m above ground (m/s)	1.7
Wind direction	171
Roughness length	0.1
Initial temperature atmosphere	297 K
Specific humidity at 2,500 m above ground level	9.5

Relative humidity at 2 m%	57
Factor of short-wave adjustment	0.5
Soil data	
Initial temperature, upper layer (0–20 cm~~)~~; ~~(~~K)	293
Initial temperature, middle layer (20–50 cm~~)~~; ~~(~~K)	293
Initial temperature, deep layer (>50 cm~~)~~; ~~(~~K)	293
Relative humidity, upper layer	30
Relative humidity, middle layer	60
Relative humidity, deep layer	60
Receptor data	
Save receptor (each min)	60 min
Building data	
Inside temperature	19.85 °C
Heat transmission of walls	1.94
Heat transmission of roofs	6
Albedo walls	0.2
Albedo roofs	0.3

Vegetation in the model domain was selected from the plant database of ENVI-met. Each plant in the study area was linked to the closest default plant provided by ENVI-met. The plant database in ENVI-met is broad and ~~generalised~~generalized and does not belong to any specific species. The height of the plant database was modified according to the vegetation height in the study area. LAD, RAD, and total depth of the root zone were not measured for each plant in the study area. However, the sensitivity analysis showed that changing these values (i.e., LAD, RAD, and total depth of the root zone) ~~had~~exerted a negligible effect on the simulated outputs. Wind speed and direction, initial air temperature, and humidity were obtained from the portable weather station installed in an open space in the study area. The roughness length and short-wave adjustment were kept at default because they represented a compact urban environment. The relative humidity on the upper layer of the soil was changed from its default value (60) to 30 to represent ~~a more~~ an accurate sample of the study area. A receptor was placed at the ~~location of the~~ equipment location in each of the seven points to compare the measured and ~~modelled~~modeled microclimatic variables.

The model had numerous output parameters, including wind speed, relative humidity, surface temperature, and Tmrt~~,~~; ~~but~~ however, air temperature was selected as the validation criterion because it is one of the most important climatic parameters that define thermal environments. Several studies have adopted a similar approach in selecting air temperature as the most important parameter in validation [53, 74].

RMSE was quantified at the selected measurement points to measure the discrepancy between the ~~modelled~~modeled and measured data. RMSE is one of the most reliable methods ~~of~~for error calculation and ~~is~~ has been widely used in previous studies [75, 76]. When the RMSE ~~approaches~~ approached zero, the model ~~exhibits~~ exhibited optimum performance. Low RMSE values ~~are~~ were captured when most variations ~~are~~ were within the observed value. Table ~~15~~ 8 shows the calculated RMSE between the simulated and measured air temperatures.

Table ~~15~~ 8. RMSE values between initial ENVI-met model and measured air temperature at different measurement points.

Simulations	RMSE at selected points						
Points	1	2	3	4	5	6	7
RMSE (measured/initial ENVI-met model)	1.42	1.26	3.14	3.55	5.25	4.62	2.40

Table ~~15~~ 8 shows that the highest error values ~~occur~~occurred at ~~points~~ Points 5 and 6, with RMSEs as high as 5.25 °C and 4.62 °C, respectively. The positioning of the data loggers in urban canyons possibly led to the high value of error at these points.

The model exhibited optimum performance at ~~points~~ Points 1, 2, and 7, with the lowest RMSE values of 1.42 °C, 1.26 °C, and 2.40 °C, respectively. The higher level of accuracy in monitoring data by the portable weather station (~~point~~ Point 1) and comfort carts (~~points~~ Points 2 and 7) compared with that of the HOBO data loggers (~~points~~ Points 3~~, 4, 5 and to~~ –6) led to lower RMSE values.

Lower discrepancy was found between the measured and ~~modelled~~modeled air temperatures compared with the other points in urban canyons at ~~point~~ Point 1, which was an open space where the portable weather station ~~is~~was fixed. Table ~~15~~ 8 shows that the initial ENVI-met model provided approximate air temperature values close to the measured data. However, calibration should be conducted to generate results that reflect the measured values at selected points. In the following section, certain input variables ~~are~~were adjusted in the configuration file in the initial ENVI-met model to check whether the accuracy of the results ~~can~~ could be improved.

Adjustment in the initial ENVI-met model

Whether altering a parameter would result in discrepancy reduction was assessed by running the initial ENVI-met model with various ranges of configuration files. The initial air temperature, relative humidity, roughness length, short-wave adjustment factor, wind speed, and albedo of building walls were modified ~~based~~ on the basis of the average climatic data recorded at the weather station (Olympic Park) closest to the selected measurement points. Table ~~16~~ 9 depicts the changes in the input variables in each run of the initial model.

Table ~~16~~ 9. Input parameters in configuration files used in various simulation runs [71].

Symbol	Changing parameter	In the initial ENVI-met model	In adjustment tests
◇	Factor of short-wave adjustment	0.5	1
+	Initial air temperature	297 K (23.8 °C)	295
✸	Relative humidity	57	55

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○	Roughness length	0.5	0.1
□	Wind	1.7	4
▽	Albedo walls	0.2	0.3
✡	Albedo roof	0.2	0.4

Table ~~17~~ 10 and Figure 9 present the calculated RMSE values for each simulation run. Table ~~17~~ 10 indicates that adjusting the input parameters improved the performance of the model. However, the magnitude of each improvement varied from one measurement point to another. The lowest RMSE levels at ~~points~~ Points 1 and 2 were due to modification in the initial air temperature and relative humidity, with RMSE values decreasing from 1.42 °C to 0.95 °C and from 1.26 °C to 0.75 °C, respectively. The lowest RMSE value at ~~point~~ Point 3 was due to adjustment in the albedo of the walls from 0.2 to 0.3, ~~thereby reducing~~ which reduced the RMSE from 3.14 °C to 2.01 °C. The same level of reduction was caused by altering the short-wave adjustment factor from 0.5 to 0.1. ~~By modifying the wind speed and albedo, the~~ The model demonstrated improved performance at ~~points~~ Points 4~~, 5, 6 and to~~ –7 by modifying the wind speed and albedo.

Table ~~17~~ 10. RMSE values in different runs of the initial ENVI-met model with altered configuration files.

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Symbol	Simulations	RMSE values at selected areas						
		1	2	3	4	5	6	7
×	Initial ENVI-met model	1.42	1.26	3.14	3.55	5.25	4.62	2.40
◇	Factor of short-wave adjustment	1.13	1.66	2.01	2.65	3.64	3.32	0.99
+	Initial air temperature	0.95	0.76	2.85	3.28	4.90	4.30	1.66
✸	Relative humidity	0.95	0.75	2.85	3.28	4.90	4.32	1.69
○	Roughness length	1.28	1.69	2.28	2.73	3.62	3.72	1.38
□	Wind speed	1.14	1.61	2.13	2.65	3.6	3.56	1.11
▽	Albedo of walls	1.14	1.68	2.01	2.65	3.62	3.31	1
✡	Albedo of walls	1.17	1.71	2.06	2.65	3.60	3.31	1.01

Figure 9 shows that performing various runs of the initial ENVI-met model improved the accuracy of the results with a different value. Thus, changing one input parameter resulted in lower RMSE at one point but increased the RMSE at the other point. Therefore, the average values were included for calibration. Table ~~17~~ 10 shows the RMSE values for all ~~the~~ configuration files. The model achieved optimum performance by altering the short-wave adjustment factor from 0.5 to 1.

The adjustment factor ranged from 0.5 (50% of unmodified ENVI-met value) to 1.5 (150%). When this value was altered to 1, the errors were reduced by 0.29, 1.13, 0.9, 1.61, 1.3, and 1.44 at ~~points~~ Points 1~~,~~ and 3~~, 4, 5, 6,~~ ~~and~~ –7, respectively.

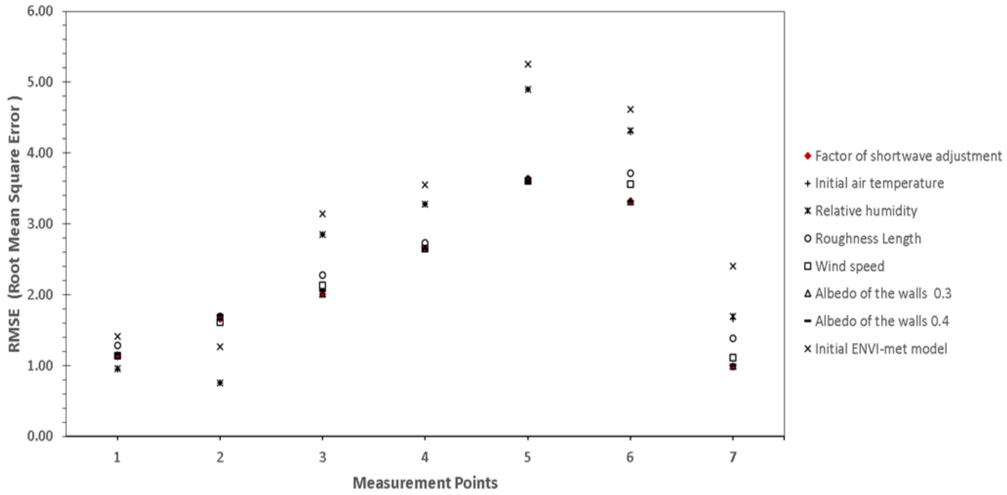

Figure 9. Calculated RMSE in different runs of initial ENVI-met model.

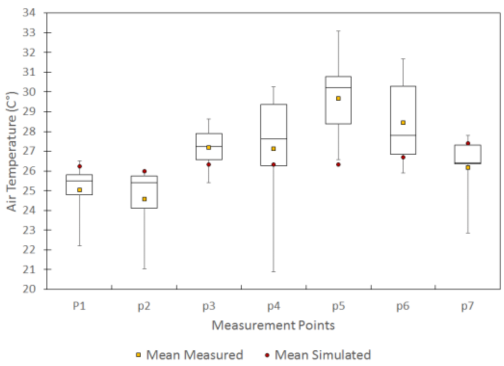

Figure 10. Mean measured and ~~mean~~ simulated values after adjustment.

Figure 10 illustrates the mean measured and ~~mean~~ simulated air temperatures after the adjustment was incorporated into the short-wave adjustment factor. The measured air temperature in the open space (~~point~~ Point 1) ~~ranged~~ ranging from 22 °C to 27 °C. The mean measured air temperature at this point was 1.1 °C lower than the mean of the adjusted simulation. ENVI-met overestimated the air temperature by 1.4 °C at ~~point~~ Point 2 (urban park) and by 1.2 °C at ~~point~~ Point 7 (under the tree canopy on Victoria Street). The opposite trend was observed in urban canyons ~~between~~among buildings, where ENVI-met underestimated the air temperature at ~~points~~ Points 3~~, 4, 5 and to~~ 6 by 0.8 °C, 0.8 °C, 3.3 °C, and 1.7 °C, respectively. The same ~~behaviour~~behavior was monitored in the study conducted in Melbourne. In [77], the diurnal variation of the ~~modelled~~modeled air temperature was overestimated by ENVI-met in areas with landscapes, whereas the ~~modelled~~modeled air temperature was underestimated ~~for the sites between~~ among sites and ~~underestimated between~~ among ~~the~~ built-up areas.

The calculated RMSE values at selected points indicated a large magnitude of error for ~~points~~ Points 3~~, 4, 5 and to~~ –6, which were located ~~between~~ among urban canyons. The larger RMSE values at these points ~~compared with~~ than those located at ~~points~~ Points 1, 2, and 7 ~~may~~might be attributed to the location of ~~point~~ Point 1 (an open space similar to the location of the portable weather station). The RMSE values between the observed and adjusted models were within the acceptable range. Therefore, the model ~~is~~was considered valid for relative comparison of urban dynamics.

The results of this study ~~show~~showed that although ENVI-met is widely used to address the questions of the ~~impact~~influence of urban development on urban climate, pedestrian thermal comfort, surface, and air temperature, ~~but not so many~~ few studies have explored the limitations associated with the use of software ~~in~~ with regard to the sensitivity of the model to different control and input parameters~~, as well as~~ and scale sensitivity analysis.

In this study, we used measured ~~vs.~~ versus simulated error metrics to test the reliability of ENVI-met in predicting ~~the~~ air temperature values. The findings of this ~~study~~work were in line with those of the studies ~~which~~ that have found that ~~solely~~ reliance on the error metric alone without including the sensitivity of the model to its own input parameters would result in higher EMSE values and therefore less accuracy in the simulated outputs~~,~~ [78-81]. ~~-~~This ~~study~~work also ~~confirms~~ confirmed the findings of the studies ~~which~~ that have found that the main ENVI-met limitation is the performance of the model in relation to the heat transfer between buildings and atmosphere~~,~~; ~~and~~ therefore, ~~have called for~~ further rigorous and comprehensive testing and verifications of this numerical ~~modelling~~modeling system are required [82, 83]. The results of this study also ~~confirms~~ verified the concerns ~~voiced~~indicated by [84] in relation to the correct wind profile in the model configuration file ~~in avoiding~~ to prevent the model from crashing caused by turbulence due to the vertical motion at the beginning of running the model. ~~Therefore, this study also highlights~~ This study highlighted the necessity to work on the wind profiles in ENVI-met ~~which~~ that ~~can~~could represent the fluctuations and variations in the prevailing wind pattern, which are common in urban areas. These limitations ~~are~~were also identified by [85]~~,~~ and must be ~~re-~~reacknowledged as the potential improvement to ENVI-met as a sophisticated urban climate ~~modelling~~modeling system.

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Conclusion

~~Given the increasing concern of the international scientific community towards global climate change, microclimate, outdoor thermal comfort, and public health this paper~~ This study aims to provide a holistic overview of various ~~modelling~~modeling systems given the increasing concern of the international scientific community toward global climate change, microclimate, outdoor thermal comfort, and public health. ~~It~~The study also focuses on the software ENVI-met~~,~~ and its reliability as one of the holistic ~~three-dimensional~~3D ~~non-~~nonhydrostatic models for ~~the simulation of~~ simulating surface–plant–air interactions. ~~which~~ This model is often used to evaluate urban environments and assess the microclimate ~~deriving~~ derived from different urban development scenarios.

~~In this study a great~~ Considerable attention was paid to the evaluation of the ~~model~~ input ~~parameters~~ and control parameters of the model in this study while describing the procedure performed for the simulations. Therefore, ~~Despite~~ despite the capabilities of ENVI-met 3.1, improvements are found necessary to ensure highly accurate results. ~~Some of the~~ Several of the limitations of ENVI-met caused by the discrepancy between the recorded and simulated values are presented ~~in the following~~as follows.

In ENVI-met, the input data ~~are~~were kept constant at the model boundary, and a logarithmic law was applied to calculate the wind profile based on the wind speed at 10 m above ground level and roughness length of the site. All calculations in the model were conducted ~~based~~ on the basis of the fixed initial transferred inputs during the simulation. Therefore, having the exact same output with the hourly recorded values from the actual site ~~is~~was unlikely. The difference between the recorded and measured values ~~can~~ could be reduced if the meteorological parameters at the boundary conditions could be adjusted. The capability of forcing climatic data should be one of the objectives in future versions of ENVI-met. The other limitation of ENVI-met was in calculating the heat storage in buildings. The heat transferred through walls ~~can~~ could be calculated by considering the conduction using wall U values.

The other drawbacks of the ENVI-met model as a microclimate analytical tool are as follows. First, the buildings in the model are not ~~parameterised~~parameterized because thermal mass and heat storage are not calculated. Moreover, the albedo and thermal transmittance cannot be separately assigned to individual building elements. ~~Thus, the~~The model is thus applicable only to daytime situations and ~~is~~ unsuitable for nocturnal cooling and UHI analysis.

This study conducted various runs of ENVI-met with different configuration files (one variable in each run was changed, and the other variables were kept constant). The results showed that adjusting the shortwave solar radiation calculated by ENVI-met based on the study site would result in a low level of difference between the simulated and measured values.

Despite the aforementioned limitations of ENVI-met, microclimate and comfort modifications ~~can~~ could be predicted, and the effect of ~~‘~~“what-if~~’~~” scenarios ~~can~~ could be evaluated. ~~One of the major challenges in modelling~~A major challenge in modeling ~~in~~ the study area using ENVI-met was the computation time. Sensitivity analysis was conducted using different numbers of grids~~:~~, that is, 1-250X250X30, 2-245X245X30, 3-240X240X30, 4-235X235X30, and 5-230X230X30. An error in running the simulations with grid numbers 1 ~~to~~ –4 was observed due to insufficient space dedicated to nesting grids. These grids ~~are~~were essential in reducing the errors caused by boundary effects and ensuring that the simulation processes ~~are not~~ were unaffected by the model borders. Thus, 230X230X30 was selected as the most appropriate number for the grids because it represented the minimum number of the grids covering the entire study area with high resolution (size/resolution) and did not cause issues in running the simulation.

Seven models for validation and adjustments on configuration files and five models for testing the sensitivity of the outputs to the type and density of the vegetation were applied to check the reliability of ENVI-met and calibrate this method against ~~the~~ field measurement. Each simulation was completed within approximately ~~one~~ 1 month. ~~Some of the~~ Several simulations were conducted simultaneously to accelerate the process~~,~~; ~~but~~ however, the overall duration for running all ~~of the~~ simulations would take approximately ~~eight~~ 8 months. This time-consuming process, particularly to examine the design scenarios at the ~~neighbourhood~~neighborhood scale, is the major limitation of ENVI-met in urban planning studies.

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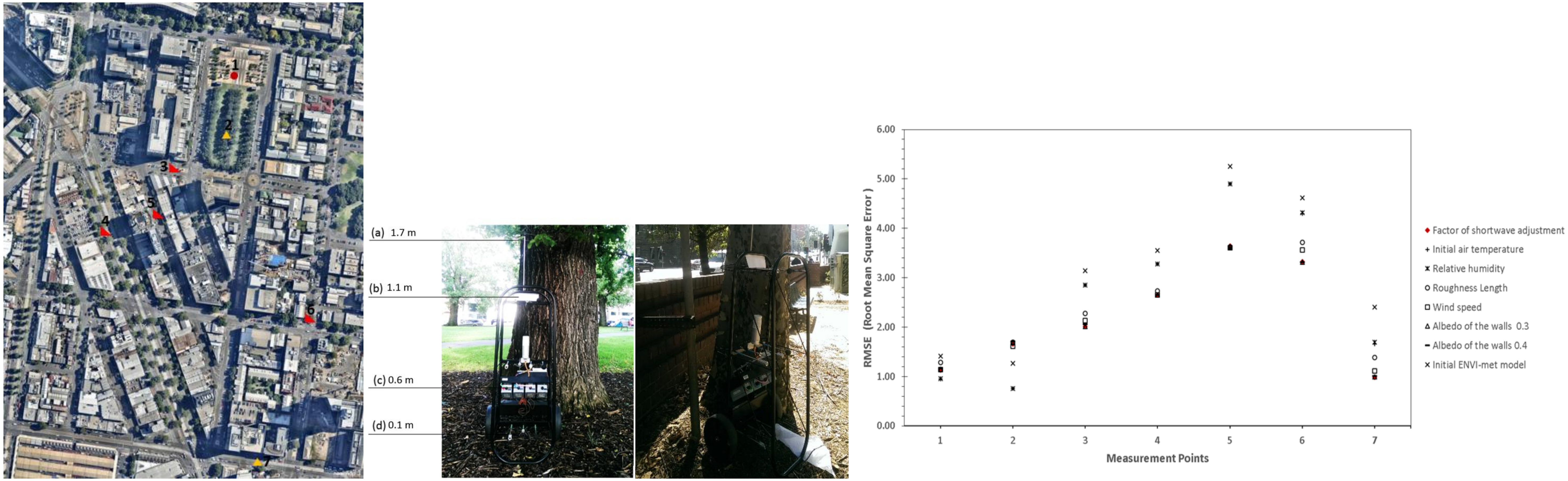
***Graphical Abstract**



Validation process of a bioclimatic modelling system from selection of the measurement points, conducting field measurement and calculation of the RMSU between the measured and simulated outputs (from left to right).

Revised Highlights Track Change

Highlights:

- The reliability of ENVI-met as one of the most popular bioclimatic tools is ~~also~~ discussed through a comprehensive review of previous validation studies.
- ~~by providing a~~ENVI-met is validated ~~comprehensive review of previous validation studies~~ ~~and~~ by conducting a field measurement in one of the fastest growing suburbs in Melbourne, Australia.
- The limitations of ENVI-met (different versions) are discussed to assist planners in carefully selecting modeling systems that can accurately address the aims and objectives of their project.
- The results showed that despite the capabilities of ENVI-met 3.1, improvements are required to produce more accurate outcomes.

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Introduction

The importance of climatic modeling as a powerful planning tool has been regularly highlighted in the literature over the last few decades because of rapid urbanization rate, global climate change, and increased heat wave rate [1]. As a result, climatic and bioclimatic modeling systems have been increasingly used to achieve the objectives of climate-sensitive urban planning.

The popularity of numerical modeling for on-site field measurements has led to increased research interest in modeling approaches [2]. This popularity is justified by the high capacity of climatic modeling to handle the complexities and nonlinearity of urban climate systems. Climatic modeling systems also enable researchers to have greater control over modeling compared with nonlinear on-site field measurements. Most importantly, these modeling systems are economically viable and efficient in saving time and resources [3-5]. Modeling approaches can forecast and predict the climatic effects of diverse "what-if" scenarios, which leads to an environmentally friendly planning scheme and an improved outdoor thermal environment for citizens [6].

On-site field measurement is a time-consuming approach that can only cover a limited number of parameters at a time. The complex interactions of 3D urban spaces and the spatial distribution of climatic parameters cannot be included simultaneously by conducting field measurements [7, 8]. However, on-site measurements are an integral part of any modeling approach due to the importance of model validation.

Nowadays, Climatic and bioclimatic modeling systems are increasingly being used to highlight the benefits of heat mitigation strategies in urban areas (e.g., use of green infrastructure, alterations on urban form and street geometry, and application of high-albedo materials). However, testing the reliability of the computational models are necessary before evaluating the effectiveness of heat mitigation scenarios. Although several previous studies have conducted limited assessment of a range of climatic and bioclimatic modeling systems for different contexts with diverse geographical and climatic backgrounds, systematic evaluation of the models and their sensitivity to inputs and control parameters remains lacking. Whether the previous studies on model validation in one part of the world provide any assurance that the model can accurately simulate the effects of heat mitigation scenarios in the other parts of the world remains unclear.

Therefore, this study aims to provide an overview of different types of climatic and bioclimatic modeling systems and briefly present their main benefits and shortcomings in calculations initially. In the second part of this study, one of the most comprehensive and widely used modeling systems, namely, ENVI-met, was selected, and its reliability in different contexts was investigated by reviewing past researches. A sensitivity analysis on inputs and control parameters was then conducted, in line with field measurements in selected areas, to test the applicability of ENVI-met in accurately simulating the influence of future urban growth on one of the fastest growing suburbs in, Melbourne.

Literature review

Climatic modeling systems

Urban climate models are defined on the basis of their scales, which range from a few centimeters to hundreds of kilometers. The five groups of climatic models based on scale are human-, room-, building-, city block-, and urban-scale models [9]. The scale of a model defines the resolution of each classification, and the resolution of each classification is highly dependent on the model scale.

Urban scale models often have the largest space resolution [10]. Therefore, planners are highly encouraged to integrate climatic modeling systems with a scale of 1:5,000 m. Only a few climatic modeling systems can consider comprehensive sets of processes (e.g., hydrological, thermal, and energy) due to the long span of time that should be spent on computation and simulation.

To address this limitation, scholars have developed models with parameterizations and simplifications, such as simple turbulence calculation [11, 12]. Some of these models target the hydrological, thermal, and energy processes at the building scale. These models are established at three levels, namely, 1D, 2D, and 3D levels, and are designed for specific circumstances [13]. Oke introduced 1D urban canyon models and suggested that they are primary numerical models that work on the basis of the energy balance of buildings [14]. Furthermore, 1D models are widely used to assess the microclimate of certain points at urban canyon at the street level. However, spatial differences cannot be detected in calculations because only surface physical properties, such as albedo, moisture level, thermal features, and roughness length, are evaluated. These models underestimate the important role of urban geometry and street orientations [15]. The predefined assumptions in 1D models include horizontally homogeneous flows and temperature fields. However, the main drawback of 1D models is that they simplify the turbulence calculation. The spatial differences within a canyon and the role of canyon geometry are also excluded in the calculation of energy exchange and in predefined assumptions.

Meanwhile, 2D models adopt certain assumptions in their calculations. Several assumptions considered in the calculations include predefined city forms and street geometries, rectangular building shapes/heights, dry urban surfaces, zero vegetation coverage, absence of latent heat, and zero heat storage in building materials [16-18].

In the last two decades, 3D models combined with computational fluid dynamics (CFD) have been identified as the strongest tools in climatic modeling systems [9]. CFD is based on equations of fluid dynamics and conservation of mass, momentum, and energy [19-21]. Climatic models are associated with CFD and include all radiation, conduction, and physical properties of a complex urban environment during calculation, which results in accurate calculation [3, 22].

In addition to urban canyon models, mathematical equations derived from field measurements are used to develop context-dependent climatic models [23]. An example of these models is the cluster thermal time constant (CTTC) [24]. Several climatic models are developed on the basis of AutoCAD for designers and used to create an accurate 3D urban environment that best represents a study area [25, 26]. These models have predefined assumptions and values for climatic parameters, such as temperature, mean radiant temperature (Tmrt), and wind speed.

Bioclimatic modeling systems

A recently proposed concept in numerical modeling systems is the integration of urban climatic knowledge into planning practices [25, 26]. The main task of bioclimatic modeling systems is to predict the outdoor thermal comfort of humans, which is a highly challenging task because of the complexities in calculating radiation fluxes received by a human body from surrounding areas in an urban setting.

RayMan [27] and SOLWEIG [28] are bioclimatic modeling systems used by scholars to quantify thermal indices, such as predicted mean vote (PMV) and physiological equivalent temperature (PET). The use of these models allows planners to assess climatic and bioclimatic parameters in urban environments and report accurate values for the outdoor thermal comfort of humans in complicated outdoor environments. Required output is one of the critical factors in selecting bioclimatic models. For instance, PMV and PET are the required outputs of SOLWEIG and RayMan, which leads to the limited use of other thermal indices, such as standard effective temperature (SET), OUT-SET, and universal thermal climate index. Goteborg University [28] established SOLWEIG, which is a radiation model that accurately measures Tmrt and PET through calculations of radiative fluxes received from all directions. However, this model presents limitations, such as the use of a simplified vegetation scheme [29]. A main limitation of SLOWEIG is that the software uses limited thermal indices in assessing thermal comfort, simplifies the vegetation scheme, calculates radiative fluxes from all directions, and neglects several climatic parameters that affect comfort.

Fluent is another bioclimatic modeling system that incorporates CFD to calculate wind speed and turbulence by considering radiation, heat balance, and evaporation modules [30]. This tool is mainly used to test aerodynamics in vehicles or indoor spaces. However, this modeling system involves long computation time.

RayMan can calculate radiation in complex urban environments [31]. This model does not require long computation time and can calculate Tmrt; however, the calculation does not include multiple reflections among buildings. RayMan can also produce a diverse range of heat indices, such as PET and PMV [32]. The main meteorological inputs for RayMan include air temperature, humidity, and wind velocity; building and vegetation information is needed to begin modeling computation. RayMan has been validated in previous studies [32]. In [32], the difference between the modeled and measured mean radiation temperatures in a semiopen area was found to be negligible (R^2 = 0.95). Several studies have reported that RayMan underestimates the value of Tmrt, especially under low solar angles, because it neglects the reflection from surrounding buildings [33]. The main limitation of this stationary model is that it cannot predict the nonstationary characteristics of a human body that moves from points A to B (sunny point to shaded point). In sum, RayMan has the disadvantages of limited thermal indices in assessing thermal comfort, failure in predicting the nonstationary thermal characteristics of a moving person, and underestimation of Tmrt at low solar angles

As another bioclimatic modeling system, TownScope is used for geometrical analysis of a 3D urban environment. The bases of calculations in this model include mean daily average air temperature, wind speed, humidity, and surface temperature [25]. However, researchers using this model cannot alter the meteorological and weather files in the calculation. The vegetation package of the system is also extremely sophisticated. The main limitations of TownScope are that it keeps the meteorological parameters constant during simulation and simplifies the vegetation scheme.

ENVI-met, a complete bioclimatic tool

This study selects ENVI-met (3.1 beta 5) [3], which is a 3D microclimatic modeling system, to achieve the research objectives. ENVI-met is one of the most sophisticated models among all urban microclimate models and it includes all energy and radiative processes in urban environments [34]. ENVI-met is used to simulate the interaction among surfaces, plants, and air in an urban environment and uses a typical resolution of 0.5 m to 10 m in space and 10 s in time. Simulations are generally performed for at least 24 h; however, the accuracy of results can be improved by running the simulations for 48 h [35].

In this study, ENVI-met is used for modeling because it can simultaneously calculate meteorological parameters, surface energy fluxes, and soil and vegetative processes within a complex urban environment by using a diverse range of urban configurations [7, 36].

In predicting outdoor thermal comfort level, ENVI-met uses Tmrt, air temperature, relative humidity, and wind velocity as inputs. This tool provides the most accurate value in predicting thermal indices.

ENVI-met is preferred for calculating outdoor thermal comfort because this bioclimatic modeling system can simulate microclimate dynamics on a daily basis. The model also predicts all radiation exchange processes, such as wind flow, turbulence, radiation flux, temperature, and humidity. ENVI-met possesses a comprehensive set of vegetation schemes and can model an urban setting in diverse contexts. This model does not consider vegetation a porous obstacle to wind and solar irradiance and includes the physiological processes of evapotranspiration and photosynthesis in calculations.

In ENVI-met, soil consists of different layers. Using high spatial (up to 0.5 m horizontally) and temporal (up to 10 s) resolutions provides a detailed illustration of microclimatic changes, especially alterations in parameters that affect comfort and urban geometry. Initiating the model with numerous outputs requires few inputs. Moreover, ENVI-met can calculate Tmrt, which is the most important parameter in determining thermal comfort.

ENVI-met has been widely applied to several studies worldwide to investigate the influences of greening [7, 37-46] and design-related parameters on microclimate [7, 42, 47, 48]. However, this tool may not provide accurate values for the required outputs. All modeling systems must be validated against field measurements to determine their capability to produce accurate outputs within an urban environment. This step is usually ignored by planning professionals because of complexities and difficulties in measuring individual variables in urban areas [49]. Several studies have established few helpful tools for comparing different scenarios [50]. Scholars have performed minor or major modifications on the input or boundary area setting to reduce the discrepancy between the simulated and measured outputs.

The following section provides a thorough review of previous validation studies. Field measurements are conducted to examine the reliability of ENVI-met in answering research questions. Table 1 presents a comparison of various modeling systems according to the required criteria in addressing the research questions.

Table 1. Comparison of various modeling systems.

Criteria	1D model	2D model	CTTC	RayMan	SOLWEIG	Fluent	TownScope	ENVI-met 3.1
Computation time	✓	✓	✓	✓	✓	×	✓	×
Considering urban	×	✓	✓	✓	✓	✓	✓	✓

geometry								
Predefined assumptions	✓	✓	✓	×	×	×	×	×
Including vegetation scheme	✓	✓	✓	×	×	✓	✓	✓
Forcing meteorological parameters	×	×	×	✓	×	×	×	×
Limited thermal indices	✓	✓	✓	✓	×	✓	✓	×
Spatial resolution	×	×	×	×	×	✓	×	✓
Limited inputs to generate meaningful outcomes	×	×	×	×	×	×	✓	✓
Calculation of Tmrt	×	×	×	✓	✓	✓	✓	✓

Accuracy of ENVI-met (Review of previous studies)

Validation with field measurement is an integral part of simulation-based studies. This section provides a comprehensive review of previous studies that have used ENVI-met as the main tool to demonstrate its accuracy. The methods and validation conducted in each study are also discussed.

A study conducted in Glasgow, UK used ENVI-met to evaluate the efficiency of various green infrastructures in addressing the overheating problem in cold-climate urban agglomeration. This validation study revealed that air temperature is overestimated during nighttime and underestimated during daytime [51]. A similar study conducted in Beijing, China evaluated the influence of landscape on microclimate variation and achieved a reasonable agreement between measured and simulated outputs (coefficient factor of 0.8087) [52]. However, a similar study conducted in Manchester, UK obtained a low coefficient factor (R^2 = 0.56) and attributed the difference between field data and simulated outputs to the elimination of various building envelopes, U values, and internal air temperature for each building [53]. Air temperature, relative humidity, wind velocity, and solar irradiance were validated at 12 points in Japan to examine the effect of greening on reducing the ambient air temperature at the pedestrian level. A cloudless sky was selected as the weather condition for a simulation day, and the spatial and temporal variabilities in the sky condition in the field measurement were ignored, thereby resulting in overestimation of solar irradiance [54]. A similar result was obtained in a study conducted in Damascus, Syria under a different climatic condition. ENVI-met slightly overestimated the solar radiation for the study areas (solar radiation was reduced to 85%). Some deviations were also observed between simulated and field data results. Therefore, input values, including initial atmospheric temperature, soil, wind speed 10 m above ground, and specific and relative humidity, were adjusted [55]. In a study in Hong Kong, ENVI-met showed a reasonable agreement between measured and simulated data for air temperature (R^2 = 0.745) and Tmrt (R^2 = 0.615) [56]. However, a similar study conducted in Manchester, UK observed a large temperature difference between measured and simulated temperatures in several receptors. The authors concluded that at least three nesting grids and five empty grids were required for a large modeling domain. Soil humidity and upper and middle temperatures were changed on the basis of a previous study conducted in this area. The model version used in this study was limited to starting temperature and wind condition as factors; therefore, the values could not be forced during the simulation [53].

Several studies validated the use of ENVI-met to determine the effect of urban shading on microclimate and outdoor thermal comfort. For instance, a study in Malaysia used ENVI-met to examine the thermal performance of an unshaded courtyard and reported agreement between modeled and real data of meteorological parameters [57]. ENVI-met was also used to evaluate the influence of adding shading trees to a street canyon on the subtropical climate of São Paulo, Brazil; in this work, the tool overestimated solar radiation decreased to 90%. The application of the same material for all buildings and the absence of heat storage in the building properties could cause a discrepancy between measured and simulated values. The coefficient factor between the measured and simulated values (based on 79 values) increased to 0.7487 after minor modifications [58].

ENVI-met was also validated in studies that assessed the effects of urban design strategies, built form, street structure, and urban form on meteorological parameters. ENVI-met was used to assess thermal comfort in different urban tissues in São Paulo, Brazil. The model underestimated the values for air temperature because the regional climatic condition was eliminated [59]. A similar study examined the effects of urban design strategies on pedestrian thermal comfort. The simulated outputs of the model did not perfectly match field data. Therefore, the model was identified as a suitable tool for comparison-based studies only. The discrepancy between measured and simulated values could be attributed to the nonnested model boundary, constant values of potential temperature and humidity at 2,500 m height during simulation without external forcing for meteorological data, and the lack of thermal mass in building properties [60].

In the Netherlands, measured and simulated air temperatures presented similar patterns on the first day of measurement. On the second day, the number and time of the hottest hours showed inconsistencies. The study conducted necessary adjustments in the model and reported that the final correlation coefficient between the two sets of data increased to 0.80 [61]. Wang and Akbari found that ENVI-met underestimated the air temperature and overestimated the relative humidity in Montreal, Canada during daytime and nighttime. The difference between measured and simulated outputs could be due to the following: (1) unified and assumed numerical values of material properties for simulation, (2) disregarding actual cloud coverage in the model and the influence of horizontal long-wave fluxes, and (3) large time intervals (10 min) for updating the sun position and the radiative fluxes from the sky [62]. Scholars in Malaysia assessed the effects of trees and ground material modification on reaching the maximum cooling effect and mitigating the heat island effect. ENVI-met underestimated the average values of air and surface temperatures. The initial temperature was increased by 2 °C to improve the correlation between measured and simulated values. The average wind speed was altered from 2.1 m/s to 1.1 m/s because of strong variation in the measured wind speed in terms of direction and speed during daytime [63]. Hamza and Dudek conducted a validation study on climatic conditions in Cairo, Egypt and found that the model underestimated the Tmrt values after sunset; the results could be due to the reduced short-wave radiation after sunset. The lack of heat storage in building properties resulted in daytime overestimation and nighttime underestimation of long-wave radiation emitted by walls. After several modifications, the coefficient values for air temperature and Tmrt increased to 0.942 and 0.916, respectively [64].

Few studies validated wind behavior by using ENVI-met. Krugler conducted a validation study on ENVI-met in Curitiba, Brazil and reported that the measured and simulated values for wind speed below 2 m/s were consistent ($R^2 = 0.80$). However, ENVI-met often overestimated the wind speed within a canyon for input wind speeds over 2 m/s ($R^2 = 0.70$) [65].

The discrepancy between measured and simulated values is not always due to the modeling incapability of ENVI-met. Different methodological approaches may also result in differences in numerical values. For instance, ENVI-met that uses reference data from weather stations is an inappropriate representative of a study site.

ENVI-met version 4.0 was used to investigate the effects of different orientations and canyon aspect ratios on street-level microclimate in Rajarhat Newtown, India. ENVI-met presented certain limitations in modeling microclimate in terms of limited domain size (100 m × 100 m grid), exclusion of single walls as a design element, and exclusion of the effect of sea breeze on wind speed [66].

A study used ENVI-met 3.1 to quantify the optimum cooling effect of trees with modified ground materials in the tropical climate of Putrajaya. A strong correlation was found between measured and modeled values and confirmed the reliability of ENVI-met in predicting existing air and ground surface temperatures [63].

A similar study assessed the capability of unshaded courtyards in cooling outdoor spaces by using different design configurations and scenarios (e.g., orientation, height and albedo of wall enclosure, and vegetation). The predicted values and real data of meteorological stations showed acceptable agreement after minor adjustments were implemented [57]. Scholars developed a recent version of ENVI-met, namely, ENVI-met V4 Beta software, to evaluate the thermal performance of different hot spots in an urban complex. The model showed R^2

of 0.69 < 1, which indicated a statistically significant correlation. Moreover, the model had a Nash–Sutcliffe coefficient of efficiency (E) of 0.91 and index of agreement (d) of 0.91, which were close to 1, which indicated perfect performance [67]. Yang [68] reviewed studies that assessed ENVI-met and observed the improved performance of the new version of ENVI-met V4 in terms of root mean square error (RMSE) values and index of agreement (d) compared with the previous version (V 3.1) for air temperature evaluation. Table 2 presents the objective of validation studies that used ENVI-met as primary software, the limitations of the model, and the validation outcomes.

Table 2 Results of previous validation studies that used ENVI-met.

Purpose of investigation	Limitation of ENVI-met	Validated ENVI-met	Reference	Location
To assess the efficiency of green infrastructure in addressing the potential overheating problem in cold-climate urban agglomerations	ENVI-met overestimated and underestimated the air temperature values during nighttime and daytime, respectively.	Modifications were needed.	[19]	Glasgow, UK
To investigate the thermal performance characteristics of unshaded courtyards in hot and humid climates	ENVI-met exhibited a high level of agreement between recorded and modeled meteorological values.	Modifications were needed.	[69]	Malaysia
To assess thermal comfort in different urban tissues	ENVI-met underestimated the values of air temperature by disregarding the regional climate effects.	Modifications were needed.	[83]	São Paulo, Brazil
To measure the effect of landscape on microclimate variation	ENVI-met achieved a reasonable agreement between the simulated and field data on air temperature with a coefficient factor of 0.8087.	Yes	[357]	Beijing, China
To assess the cooling effects of trees and cool roofs on a residential neighborhood	ENVI-met showed RMSEs of 1.41 °C (mesic), 1.81 °C (oasis), and 2.00 °C (xeric) for air temperature at 2 m above the ground level.	Yes	[367]	Phoenix, US
To assess the effects of various building geometries in four typical urban districts on outdoor temperature and comfort	ENVI-met underestimated the air temperature and overestimated the relative humidity for daytime and nighttime. The numerical values of the material properties for the simulation were unified and assumed. The actual cloud coverage was ignored in the model, the effect of horizontal long-wave fluxes was ignored, and large time steps (10 min) were used to update the sun position and radiative fluxes from the sky. After adjustments, the coefficient values for air temperature and relative humidity reached 0.78 and 0.7, respectively.	Modifications were needed.	[368]	Montreal, Canada

To investigate the effect of adding shading trees on a street canyon	ENVI-met overestimated the solar radiation for the São Paulo condition. Therefore, solar radiation was reduced to 90%. This discrepancy was attributed to the application of the same material for all buildings and the absence of heat storage in building properties. After minor modifications, the coefficient factor between measured and simulated values (based on 79 values) was improved to 0.7487.	Modifications were needed.	[275]	São Paulo, Brazil
To evaluate the effects of trees and ground material modification on maximizing the cooling effect and mitigating the heat island effect	ENVI-met underestimated the average values of air and surface temperatures. Therefore, the initial temperature was increased by 2 °C to achieve improved correlation between measured and simulated values. The average wind speed changed from 2.1 m/s to 1.1 m/s because the measured wind speed and direction varied strongly during the day.	Modifications were needed.	[364]	Malaysia
To simulate outdoor air temperature, Tmrt, wind speed, and relative humidity	The variations in measured and modeled air temperatures were similar, and their final correlation coefficient was 0.80 after the adjustment.	Modifications were needed.	[362]	The Netherlands
To evaluate the microclimate of an outdoor urban form	ENVI-met underestimated Tmrt after sunset hours because of the reduced short-wave radiation after sunset. The lack of heat storage in building properties in ENVI-met led to daytime overestimation and nighttime underestimation of long-wave radiation emitted by walls. After the modifications, the coefficient values for air temperature and Tmrt reached 0.942 and 0.916, respectively.	Modifications were needed.	[365]	Cairo, Egypt
To evaluate the effects of various greening scenarios on microclimate on the block and neighborhood scales	The regression analysis between measured and simulated air temperatures did not show a reasonable agreement (R^2 = 0.56). The model did not allow for variations in building envelope, U values, or internal temperatures for individual buildings. The model also did not allow forcing of weather variables. The model had a long running time.	Modifications were needed.	[358]	Manchester, UK
To assess the effect of greening on lowering the ambient air temperature at the pedestrian level	Air temperature, relative humidity, wind velocity, and solar irradiance were validated at 12 points by using on-site measurements. ENVI-met overestimated solar irradiance. Spatial and temporal differences were not recorded during the field measurement. Therefore, a cloudless sky was selected as the weather condition for a simulation day, which led to the deviation between measured and simulated solar values.	Modifications were needed.	[369]	Japan
To evaluate the effects of landscape elements on thermal comfort for detached buildings	ENVI-met tended to slightly overestimate the solar radiation in the study area, which reduced the solar radiation to 85%. Some deviations were also recorded between simulated and field data. Therefore, input values, including initial atmospheric temperature, soil, wind speed at 10 m above ground level, and specific and relative humidity, were adjusted.	Modifications were needed.	[370]	Damascus, Syria
To simulate near-ground air temperature in a typical residential neighborhood	ENVI-met achieved a reasonable agreement between the simulated and field data for air temperature 2 m above ground.	Yes	[21]	Phoenix, US
To evaluate the effect of downtown greening on microclimatic data	ENVI-met achieved a reasonable agreement between the measured and simulated data for air temperature (R^2 = 0.745) and Tmrt (R^2 = 0.615).	Yes	[371]	Hong Kong
To investigate the effects of urban design strategies on pedestrian thermal comfort	The discrepancy between measured and simulated values could be attributed to the nonnested model boundary, the constant values of the potential temperature and humidity at 2,500 m above ground during the simulation without external forcing for the meteorological data, and the lack of thermal mass in building properties.	Modifications were needed.	[274]	Shanghai, China

To assess the effect of vegetation on temperature reduction during extreme heat events	The simulation depended on validating air temperature by collecting data from Phoenix, US, with vegetation and microclimatic conditions similar to those in the study area.	Yes	[288]	Phoenix, US
To evaluate the effects of seven greenspace scenarios on microclimate	A large temperature difference was observed between the measured and simulated temperatures in several receptors. The ENVI-met documentation indicated that at least three nesting grids and five empty grids were required for a large modeling domain. Soil humidity and upper and middle temperatures were changed according to a previous study [62]. The values could not be forced during the simulation, given that the model version used in this study was limited to starting temperature and wind condition.	Modifications were needed.	[358]	Manchester, UK
To assess the effect of street orientation on prevailing winds and its consequences on ventilation and wind speed at the pedestrian level	The measured and simulated values were consistent (R^2 = 0.80) for wind speeds below 2 m/s. However, ENVI-met overestimated the wind speed within a canyon for input wind speeds over 2 m/s (R^2 = 0.70).	Modifications were needed.	[366]	Curitiba, Brazil
To explore the effect of architectural design on thermal performance in outdoor environments	An insignificant difference was observed between air temperature and wind speed across canyons because of limited thermal heat storage in buildings.	Modifications were needed.	[39]	Algeria

Methodology

In this section, one of the fastest growing suburbs in Melbourne that will be the subject of rapid urban development in the future is studied. One of the visions of Melbourne City Council for future urban developments is to quantify the thermal and climatic consequences of implementing the proposed urban growth scenarios. Therefore, this section explains the validation process for the model that will be used as the base for future urban growth scenarios and assess the reliability of ENVI-met in accurately modeling simulated outputs.

The methodology section is divided into two parts. In the first section, description of the study area, selection of measurement points and their physical characteristics, process of field measurements, equipment used to conduct field measurements, and monitored values are explained. The second part discusses the simulation approach, the establishment of the model with accurate inputs and configuration parameters, and the comparison of the results of the simulated and measured values through RMSE calculation. Finally, the validation process of the model and the adjustments needed for the control parameters are described.

Study area and field measurements

City North (Carlton), Melbourne, which is subject to future urban renewal and development, was selected as the study area. Seven points with diverse design features were selected to begin the field measurements. The selected points included two sites with varying street widths and a similar orientation, two urban sites with different street orientations and a similar H/W ratio, two urban canyons under a tree canopy (one was located in an urban park and the other under a tree canopy on a street), and a reference control site in an open space area. Each site was positioned in predominantly mixed-use (residential–commercial) areas that are subject to future urban development. Figure 1 shows the location and position of each measurement point in the site. Climatic parameters were measured in the middle part of each canyon. For certain points, the installation of HOBO data loggers was infeasible due to safety and security reasons. However, none of the HOBO data loggers were obstructed or shaded by trees and other buildings.

Figure 1. Location of selected points for on-site measurement (Source: [69]).

Measurement was conducted for peak warm weather in Melbourne. Field measurements were performed in January because this month has the hottest days throughout the year and the air temperature can reach 38.8 °C. Although the climate data from the Melbourne Olympic Park in January 2015 identified January 2 and 3 as two of the hottest days of the month, field measurement was conducted on these days due to the lower wind speeds in January 5 and 6. The purpose was to conduct modeling and simulation when warmer urban temperatures are more likely to induce human thermal stress, and climate is associated with high air temperature and low wind speed. Figure 2 illustrates the air temperature variation recorded at the Melbourne Olympic Park weather station in January 2015.

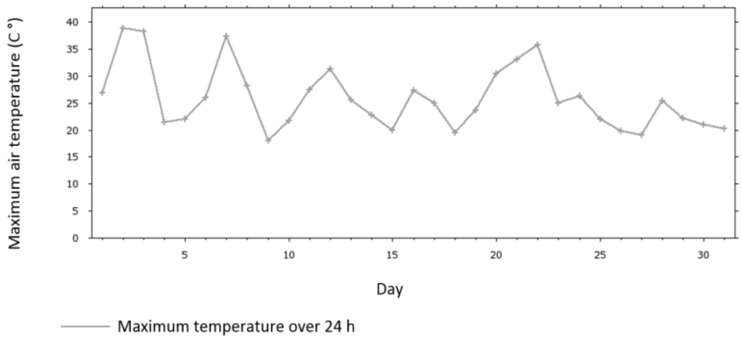


Figure 2. Maximum recorded air temperatures at Melbourne Olympic Park (Station number: 086338) in January 2015 (Source: [70]).

From January 5, 2015 at 7:00 to January 6, 2015 at 19:00, on-site field measurements were conducted under sunny and clear skies. A portable weather station was installed 3 m above the ground. Four HOBO onset data loggers (2 m above the ground) and two comfort carts were installed at selected points in the study area to record air temperature. A Nikon Coolpix 5400 camera with a fisheye converter and a 180° angle of view was used to capture sky-view factor images at the measurement points. Measurements were collected from a weather station, comfort carts, and HOBO onset data loggers at 1 h, 15 min, and 5 min intervals, respectively. The simulated hourly outputs were validated by converting all the recorded climatic variables into hourly data.

Point 1 was an open area with asphalt pavement and had almost no obstruction to the sky. This point was operated as a regional weather station for the field measurement. Point 2 was located under a dense tree canopy with 20 m height and a distinct crown layer at the University Square Park. This point was covered with a grass surface and had minimal exposure to the sky because of the shading by the surrounding trees. Point 3 was located in the middle of an east–west-oriented canyon with asphalt pavement. This site was surrounded by medium-height (two to three stories) residential units and a few recently built high-rise buildings. Point 4 was located in the middle of the NW–SE-oriented boulevard with vegetated areas in the middle of the canyon. The data logger at this point was installed on a pole in the middle of the boulevard on top of the planted area. This point was not shaded by any tree. The surface was covered by grass, and the canyon was wider than that in all other sites. This site comprised buildings with varying heights of 2 to 12 stories. Point 5 was located in an asphalt-paved urban canyon with an orientation similar to that of Point 4. However, the street canyon at Point 5 was narrower than that at Point 4. Similar to Point 4, at Point 5, building heights ranged from 2 to 12 stories. As a result, Point 5 had a higher H/W ratio than Point 4. Point 6 was located in an asphalt-paved canyon perpendicular to the canyon at Point 3. The width of streets at Points 3 and 6 was almost equal; however, the taller buildings at Point 6 resulted in a higher H/W ratio at this point. A construction site and an urban park were located on both sides of the street at Point 6. Point 7 was located under a 20 m-high average dense tree canopy on Victoria Street. The surface was covered with grass, and the building height varied from 2 to 24 stories.

These points were selected to cover various urban canyons with different features, such as H/W ratio, surface material, proximity to vegetated areas, and SVF. For instance, Points 4 and 5 were situated in urban canyons with the same orientation (NW–SE) but had different street widths and H/W ratios. Points 3 and 6 were located in street canyons with almost equal H/W ratio but different orientations (perpendicular to each other). Points 1 and 7 were located below the canopy of dense trees, with the former located in an urban park and the latter located on Victoria Street. Table 3 shows the detailed characteristics of the selected measurement points. Table 4 presents the images of the selected canyons and corresponding SVF images.

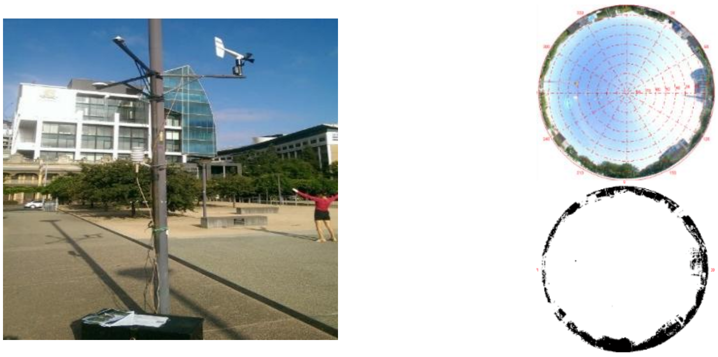
Table 3. Characteristics of selected points for on-site measurement [71].

Point	Site characteristic	SVF value	Surface type	H/W ratio	Height of measurement	Equipment used	Symbol
1	Open space	0.9	Asphalt	_	3 m	Portable weather station	△
2	Under a tree canopy in a park	0.2	Grass	_	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	●
3	E–W-oriented street canyon	0.5	Asphalt	0.5	2 m	HOBO data logger	◣
4	NW–SE-oriented street canyon	0.8	Grass	0.8	2 m	HOBO data logger	◣
5	NW–SE-oriented street canyon	0.4	Asphalt	2.7	2 m	HOBO data logger	◣
6	N–S-oriented street canyon	0.6	Asphalt	0.4	2 m	HOBO data logger	◣
7	Under a tree canopy in a street	0.3	Grass	1.4	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	●

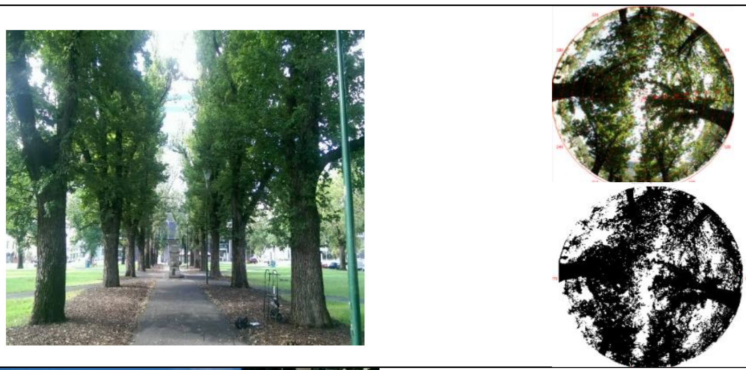
Table 4. Selected canyons and SVF images of measurement points.

Point	Selected canyon	SVF image

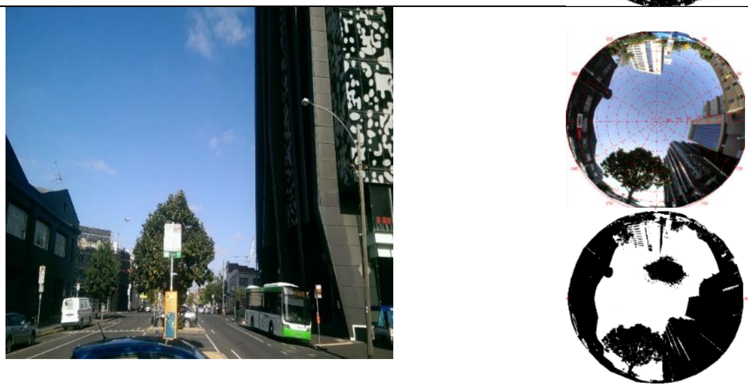
Point 1



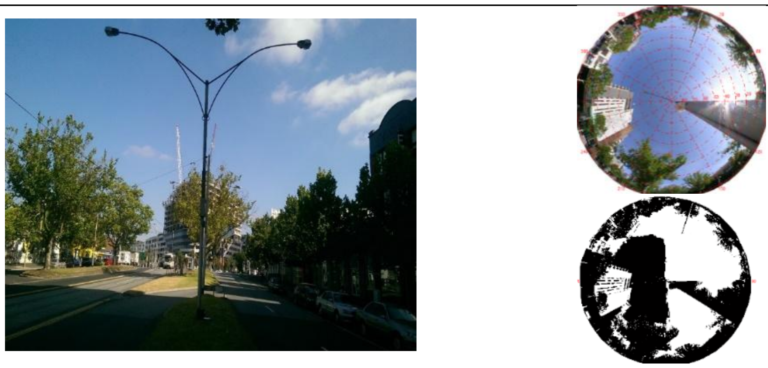
Point 2



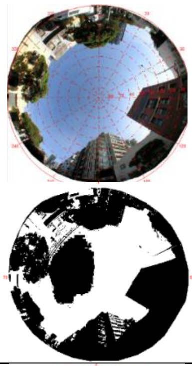
Point 3



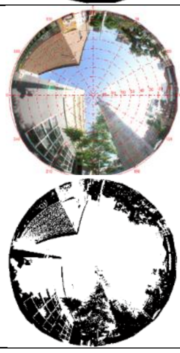
Point 4



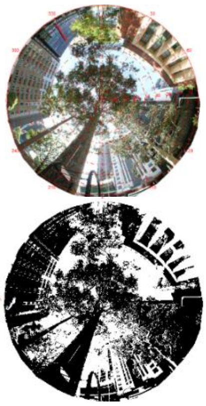
Point 5



Point 6



Point 7



Equipment used for on-site measurement

Comfort carts, HOBO data loggers, a portable weather station, and a fisheye camera were used to capture SVF images. The comfort study recommended the measurements to be taken at 1.1 m. However, the HOBO data loggers and weather station were installed at 2 m and 3 m above the ground level, respectively, to avoid sensor damage in the study area. According to a study conducted by Oke, the measurement equipment should be installed at the standard observational height, which could vary from 1.25 m to 2 m. Oke also observed minimal gradients for air temperature measured throughout the urban canopy layer [72].

The accuracy ranges of the used equipment complied with ISO 7726 recommendations. HOBO data loggers were used at Points 3–6, and a fixed meteorological monitoring station was installed at Point 1 as reference.

Various climatic parameters were recorded using different sensors in the station. Wind monitors, temperature and humidity sensors, and global illuminance and solar radiation sensors were installed in the weather station. Simulation was initialized using the recorded air temperature, relative humidity, wind speed, and wind direction at Point 1 as the initial climatic variables.

A comfort car was used in the measurement. This tool was designed to assess thermal environments inside buildings according to procedures and protocols in the thermal comfort standard of ASHRAE [73]. The environment was measured by each cart simultaneously at four heights within the occupied zone. These heights are coded with the following colors:

• [Black] HEAD (1.7 m above floor level corresponds to the head of a standing person) (a)

• [Red] HI (1.1 m above floor level corresponds to the head of a seated person) (b)

• [Blue] MID (0.6 m above floor level corresponds to the waist of a seated person) (c)

• [Green] LO (0.1 m above floor level corresponds to the ankles of a seated person) (d)

Figure 3 presents a comfort cart installed at Point 2 under the canopy of a tree in an urban park at the University Square. Figure 3 shows four different heights of measurement in the comfort cart. Figure 4 depicts the second comfort cart installed under the tree canopy on Victoria Street (Point 7).

Figure 3. Comfort cart at Point 2 under the shade of a tree canopy in an urban park (University Square).

Figure 4. Comfort cart at Point 7 under the shade of a tree canopy on Victoria Street.

Hemispherical digital images were taken with a fisheye lens camera from the center of each urban canyon, and the SVF value at each selected point in the urban canyons was calculated. Figure 5 shows that SOLWEIG 1D was used to convert the SVF images into their corresponding SVF values at each point.

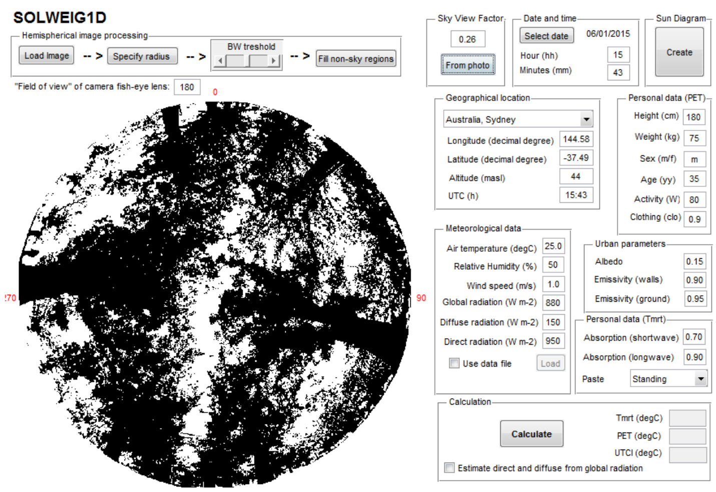


Figure 5. Calculating SVF value from fisheye camera images in SOLWEIG 1D.

Results of on-site measurement

The climatic data show fluctuations in air temperature, relative humidity, and wind speed in the study area during the measurement dates. This variation is observed not only at different times of the measurement but also at different measurement points. The difference in the average recorded climatic data at different measurement points can be attributed to the accuracy of the equipment, the location of the equipment during the measurement, the proximity to construction sites, and the geometry of each canyon.

The mean daytime air temperature varies from 24 °C to 29.6 °C across the seven measurement points. This fluctuation is significantly lower under the nighttime condition, during which the maximum difference in the monitored data is only 0.6 °C. Similar to daytime and nighttime air temperature patterns, the relative humidity during the day shows a higher level of fluctuation than that during the night. The mean daytime relative humidity ranges from 45% to 58%, and the nighttime relative humidity varies from 83% to 87%. Wind speed has the lowest level of variation; only a 1.7 m/s difference is observed between the highest and lowest wind speed values at different measurement points. Table 5 lists the maximum and minimum measured air temperatures, relative humidities, and wind speeds during the measurement. Figure 6 shows the variations in air temperature at different measurement points. Figure 7 presents the variations in relative humidity at different measurement points. Figure 8 shows the variations in wind speed.

Table 5. Differences in measured data at various measurement points during daytime and nighttime.

Climatic parameter	Min		Max		(Max–Min)	
	Day	Night	Day	Night	Day	Night
Air temperature (°C)	24.5	19.8	29.6	20.5	5.1	0.7
Relative humidity (%)	45	83.3	58	87.2	13	3.9
Wind speed (m/s)	0.3		2		1.7	

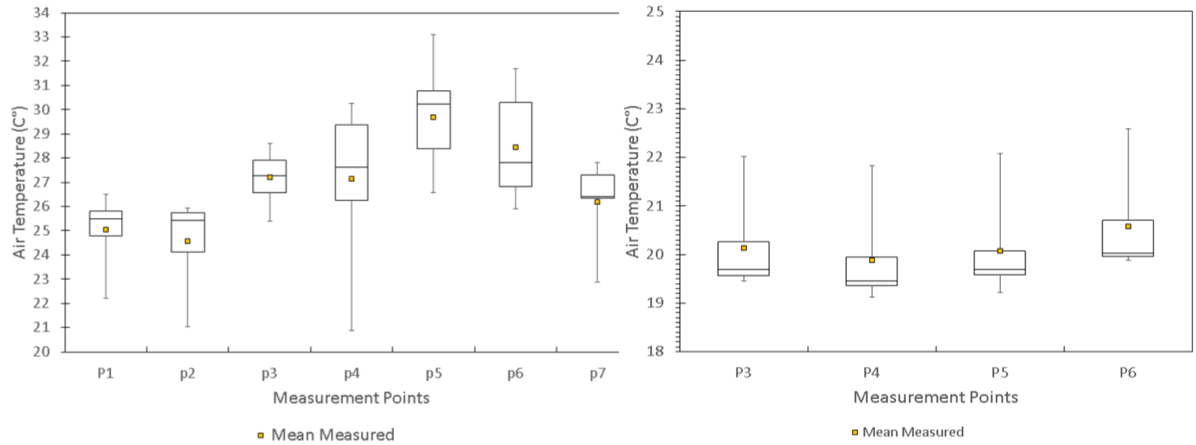


Figure 6. Monitored air temperature at selected measurement points during daytime (9:00–17:00; left) and nighttime (22:00–5:00; right).

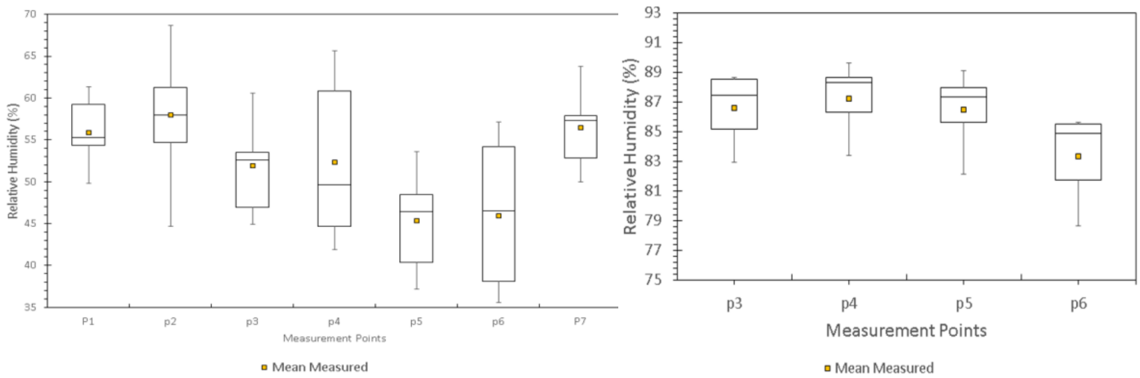


Figure 7. Monitored relative humidity at selected measurement points during daytime (9:00–17:00; left) and nighttime (22:00–5:00; right).

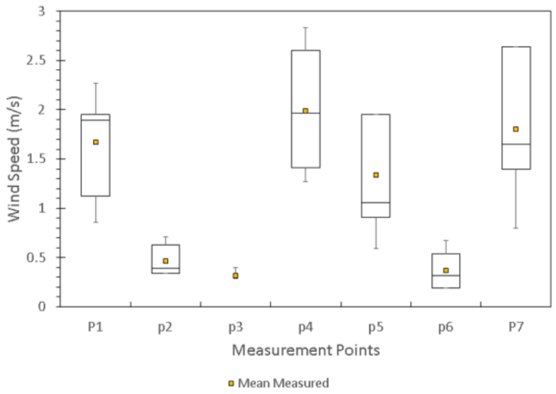


Figure 8. Monitored wind speed at daytime (9:00–17:00).

Simulation approach and verification against field measurements

The model of the study area was constructed using the area input file (Table 6) and configuration file (Table 7). The configuration file was used as starting point to run the initial ENVI-met model as closely as possible to the observed air temperature determined at each measurement point.

Table 6. Initial setup of the model domain (area input file) [71].

Input setup	Value
Orientation (degree from the north)	7
Number of x grids	230
Number of y grids	230
Number of z grids	30
Size of grid cell in m (dx)	3
Size of grid cell in m (dy)	3
Size of grid cell in m (dz)	2
Name of location	Melbourne, Australia
Position on the Earth	Latitude (−37.49), longitude (144.58)
Number of nesting grids	5
Soil profile for nesting grids	Soils A and B = Loamy soil

Table 7. Settings for the configuration file used to run the initial ENVI-met model [71].

Input for configuration file	Value
Start simulation	1:00, January 6, 2015
Total simulation time in hours	48 h
Save model state (each min)	60
Wind speed at 10 m above ground (m/s)	1.7
Wind direction	171
Roughness length	0.1
Initial temperature atmosphere	297 K
Specific humidity at 2,500 m above ground level	9.5
Relative humidity at 2 m%	57
Factor of short-wave adjustment	0.5
Soil data	
Initial temperature, upper layer (0–20 cm; K)	293
Initial temperature, middle layer (20–50 cm; K)	293

Initial temperature, deep layer (>50 cm; K)	293
Relative humidity, upper layer	30
Relative humidity, middle layer	60
Relative humidity, deep layer	60
Receptor data	
Save receptor (each min)	60 min
Building data	
Inside temperature	19.85 °C
Heat transmission of walls	1.94
Heat transmission of roofs	6
Albedo walls	0.2
Albedo roofs	0.3

Vegetation in the model domain was selected from the plant database of ENVI-met. Each plant in the study area was linked to the closest default plant provided by ENVI-met. The plant database in ENVI-met is broad and generalized and does not belong to any specific species. The height of the plant database was modified according to the vegetation height in the study area. LAD, RAD, and total depth of the root zone were not measured for each plant in the study area. However, the sensitivity analysis showed that changing these values (i.e., LAD, RAD, and total depth of the root zone) exerted a negligible effect on the simulated outputs. Wind speed and direction, initial air temperature, and humidity were obtained from the portable weather station installed in an open space in the study area. The roughness length and short-wave adjustment were kept at default because they represented a compact urban environment. The relative humidity on the upper layer of the soil was changed from its default value (60) to 30 to represent an accurate sample of the study area. A receptor was placed at the equipment location in each of the seven points to compare the measured and modeled microclimatic variables.

The model had numerous output parameters, including wind speed, relative humidity, surface temperature, and Tmrt; however, air temperature was selected as the validation criterion because it is one of the most important climatic parameters that define thermal environments. Several studies have adopted a similar approach in selecting air temperature as the most important parameter in validation [53, 74].

RMSE was quantified at the selected measurement points to measure the discrepancy between the modeled and measured data. RMSE is one of the most reliable methods for error calculation and has been widely used in previous studies [75, 76]. When the RMSE approached zero, the model exhibited optimum performance. Low RMSE values were captured when most variations were within the observed value. Table 8 shows the calculated RMSE between the simulated and measured air temperatures.

Table 8. RMSE values between initial ENVI-met model and measured air temperature at different measurement points.

Simulations	RMSE at selected points						
Points	1	2	3	4	5	6	7

RMSE (measured/initial ENVI-met model)	1.42	1.26	3.14	3.55	5.25	4.62	2.40

Table 8 shows that the highest error values occurred at Points 5 and 6, with RMSEs as high as 5.25 °C and 4.62 °C, respectively. The positioning of the data loggers in urban canyons possibly led to the high value of error at these points.

The model exhibited optimum performance at Points 1, 2, and 7, with the lowest RMSE values of 1.42 °C, 1.26 °C, and 2.40 °C, respectively. The higher level of accuracy in monitoring data by the portable weather station (Point 1) and comfort carts (Points 2 and 7) compared with that of the HOBO data loggers (Points 3–6) led to lower RMSE values.

Lower discrepancy was found between the measured and modeled air temperatures compared with the other points in urban canyons at Point 1, which was an open space where the portable weather station was fixed. Table 8 shows that the initial ENVI-met model provided approximate air temperature values close to the measured data. However, calibration should be conducted to generate results that reflect the measured values at selected points. In the following section, certain input variables were adjusted in the configuration file in the initial ENVI-met model to check whether the accuracy of the results could be improved.

Adjustment in the initial ENVI-met model

Whether altering a parameter would result in discrepancy reduction was assessed by running the initial ENVI-met model with various ranges of configuration files. The initial air temperature, relative humidity, roughness length, short-wave adjustment factor, wind speed, and albedo of building walls were modified on the basis of the average climatic data recorded at the weather station (Olympic Park) closest to the selected measurement points. Table 9 depicts the changes in the input variables in each run of the initial model.

Table 9. Input parameters in configuration files used in various simulation runs [71].

Symbol	Changing parameter	In the initial ENVI-met model	In adjustment tests
◇	Factor of short-wave adjustment	0.5	1
+	Initial air temperature	297 K (23.8 °C)	295
✸	Relative humidity	57	55
o	Roughness length	0.5	0.1
□	Wind	1.7	4
▽	Albedo walls	0.2	0.3
✡	Albedo roof	0.2	0.4

Table 10 and Figure 9 present the calculated RMSE values for each simulation run. Table 10 indicates that adjusting the input parameters improved the performance of the model. However, the magnitude of each improvement varied from one measurement point to another. The lowest RMSE levels at Points 1 and 2 were due to modification in the initial air temperature and relative humidity, with RMSE values decreasing from 1.42 °C to 0.95 °C and from 1.26 °C to 0.75 °C, respectively. The lowest RMSE value at Point 3 was due to adjustment in the albedo of the walls from 0.2 to 0.3, which reduced the RMSE from 3.14 °C to 2.01 °C. The same level of reduction was caused by altering the short-wave adjustment factor from 0.5 to 0.1. The model demonstrated improved performance at Points 4–7 by modifying the wind speed and albedo.

Table 10. RMSE values in different runs of the initial ENVI-met model with altered configuration files.

Symbol	Simulations	RMSE values at selected areas						
		1	2	3	4	5	6	7
×	Initial ENVI-met model	1.42	1.26	3.14	3.55	5.25	4.62	2.40
◇	Factor of short-wave adjustment	1.13	1.66	2.01	2.65	3.64	3.32	0.99
+	Initial air temperature	0.95	0.76	2.85	3.28	4.90	4.30	1.66
✶	Relative humidity	0.95	0.75	2.85	3.28	4.90	4.32	1.69
o	Roughness length	1.28	1.69	2.28	2.73	3.62	3.72	1.38
□	Wind speed	1.14	1.61	2.13	2.65	3.6	3.56	1.11
▽	Albedo of walls	1.14	1.68	2.01	2.65	3.62	3.31	1
✡	Albedo of walls	1.17	1.71	2.06	2.65	3.60	3.31	1.01

Figure 9 shows that performing various runs of the initial ENVI-met model improved the accuracy of the results with a different value. Thus, changing one input parameter resulted in lower RMSE at one point but increased the RMSE at the other point. Therefore, the average values were included for calibration. Table 10 shows the RMSE values for all configuration files. The model achieved optimum performance by altering the short-wave adjustment factor from 0.5 to 1.

The adjustment factor ranged from 0.5 (50% of unmodified ENVI-met value) to 1.5 (150%). When this value was altered to 1, the errors were reduced by 0.29, 1.13, 0.9, 1.61, 1.3, and 1.44 at Points 1 and 3–7, respectively.

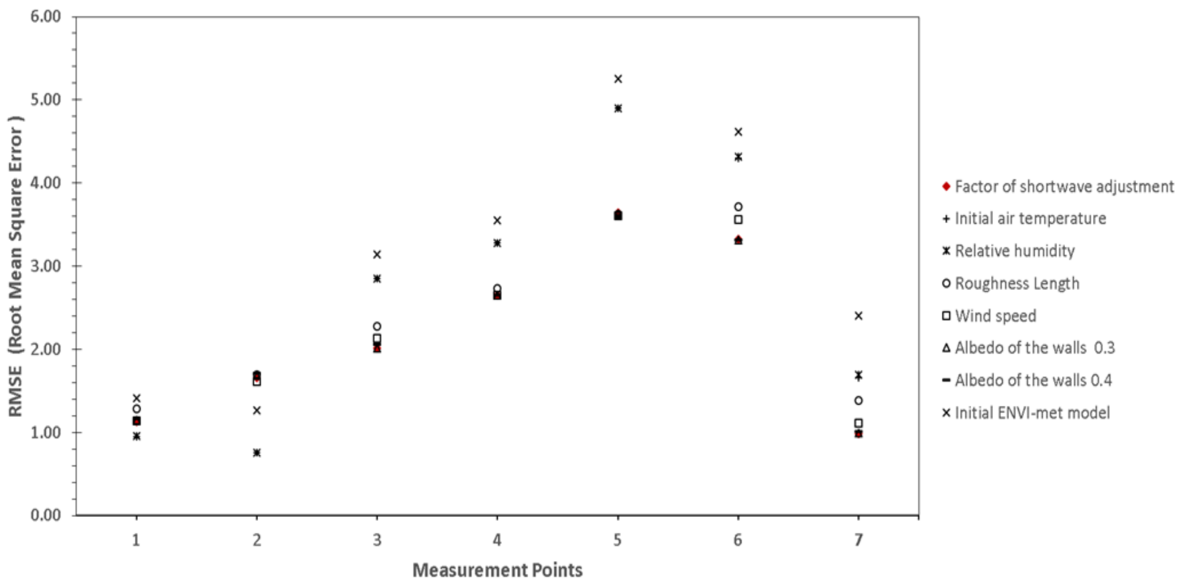


Figure 9. Calculated RMSE in different runs of initial ENVI-met model.

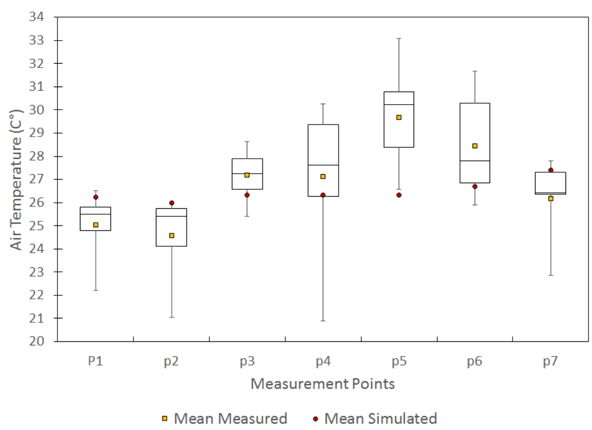


Figure 10. Mean measured and simulated values after adjustment.

Figure 10 illustrates the mean measured and simulated air temperatures after the adjustment was incorporated into the short-wave adjustment factor. The measured air temperature in the open space (Point 1) ranging from 22 °C to 27 °C. The mean measured air temperature at this point was 1.1 °C lower than the mean of the adjusted simulation. ENVI-met overestimated the air temperature by 1.4 °C at Point 2 (urban park) and by 1.2 °C at Point 7 (under the tree canopy on Victoria Street). The opposite trend was observed in urban canyons among buildings, where ENVI-met underestimated the air temperature at Points 3–6 by 0.8 °C, 0.8 °C, 3.3 °C, and 1.7 °C, respectively. The same behavior was monitored in the study conducted in Melbourne. In [77], the diurnal variation of the modeled air temperature was overestimated by ENVI-met in areas with landscapes, whereas the modeled air temperature was underestimated among sites and among built-up areas.

The calculated RMSE values at selected points indicated a large magnitude of error for Points 3–6, which were located among urban canyons. The larger RMSE values at these points than those located at Points 1, 2, and 7 might be attributed to the location of Point 1 (an open space similar to the location of the portable weather station). The RMSE values between the observed and adjusted models were within the acceptable range. Therefore, the model was considered valid for relative comparison of urban dynamics.

The results of this study showed that although ENVI-met is widely used to address the questions of the influence of urban development on urban climate, pedestrian thermal comfort, surface, and air temperature, few studies have explored the limitations associated with the use of software with regard to the sensitivity of the model to different control and input parameters and scale sensitivity analysis.

In this study, we used measured versus simulated error metrics to test the reliability of ENVI-met in predicting air temperature values. The findings of this work were in line with those of the studies that have found that reliance on the error metric alone without including the sensitivity of the model to its own input parameters would result in higher EMSE values and therefore less accuracy in the simulated outputs [78-81]. This work also confirmed the findings of the studies that have found that the main ENVI-met limitation is the performance of the model in relation to the heat transfer between buildings and atmosphere; therefore, further rigorous and comprehensive testing and verifications of this numerical modeling system are required [82, 83]. The results of this study also verified the concerns indicated by [84] in relation to the correct wind profile in the model configuration file to prevent the model from crashing caused by turbulence due to the vertical motion at the beginning of running the model. This study highlighted the necessity to work on the wind profiles in ENVI-met that could represent the fluctuations and variations in the prevailing wind pattern, which are common in urban areas. These limitations were also identified by [85] and must be reacknowledged as the potential improvement to ENVI-met as a sophisticated urban climate modeling system.

Conclusion

This study aims to provide a holistic overview of various modeling systems given the increasing concern of the international scientific community toward global climate change, microclimate, outdoor thermal comfort, and public health. The study also focuses on the software ENVI-met and its reliability as one of the holistic 3D nonhydrostatic models for simulating surface–plant–air interactions. This model is often used to evaluate urban environments and assess the microclimate derived from different urban development scenarios.

Considerable attention was paid to the evaluation of the input and control parameters of the model in this study while describing the procedure performed for the simulations. Therefore, despite the capabilities of ENVI-met 3.1, improvements are found necessary to ensure highly accurate results. Several of the limitations of ENVI-met caused by the discrepancy between the recorded and simulated values are presented as follows.

In ENVI-met, the input data were kept constant at the model boundary, and a logarithmic law was applied to calculate the wind profile based on the wind speed at 10 m above ground level and roughness length of the site. All calculations in the model were conducted on the basis of the fixed initial transferred inputs during the simulation. Therefore, having the exact same output with the hourly recorded values from the actual site was unlikely. The difference between the recorded and measured values could be reduced if the meteorological parameters at the boundary conditions could be adjusted. The capability of forcing climatic data should be one of the objectives in future versions of ENVI-met. The other limitation of ENVI-met was in calculating the heat storage in buildings. The heat transferred through walls could be calculated by considering the conduction using wall U values.

The other drawbacks of the ENVI-met model as a microclimate analytical tool are as follows. First, the buildings in the model are not parameterized because thermal mass and heat storage are not calculated. Moreover, the albedo and thermal transmittance cannot be separately assigned to individual building elements. The model is thus applicable only to daytime situations and unsuitable for nocturnal cooling and UHI analysis.

This study conducted various runs of ENVI-met with different configuration files (one variable in each run was changed, and the other variables were kept constant). The results showed that adjusting the shortwave solar radiation calculated by ENVI-met based on the study site would result in a low level of difference between the simulated and measured values.

Despite the aforementioned limitations of ENVI-met, microclimate and comfort modifications could be predicted, and the effect of “what-if” scenarios could be evaluated. A major challenge in modeling the study area using ENVI-met was the computation time. Sensitivity analysis was conducted using different numbers of grids, that is, 1-250X250X30, 2-245X245X30, 3-240X240X30, 4-235X235X30, and 5-230X230X30. An error in running the simulations with grid numbers 1–4 was observed due to insufficient space dedicated to nesting grids. These grids were essential in reducing the errors caused by boundary effects and ensuring that the simulation processes were unaffected by the model borders. Thus, 230X230X30 was selected as the most appropriate number for the grids because it represented the minimum number of the grids covering the entire study area with high resolution (size/resolution) and did not cause issues in running the simulation.

Seven models for validation and adjustments on configuration files and five models for testing the sensitivity of the outputs to the type and density of the vegetation were applied to check the reliability of ENVI-met and calibrate this method against field measurement. Each simulation was completed within approximately 1 month. Several simulations were conducted simultaneously to accelerate the process; however, the overall duration for running all simulations would take approximately 8 months. This time-consuming process, particularly to examine the design scenarios at the neighborhood scale, is the major limitation of ENVI-met in urban planning studies.

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Table 1 Comparison of various modelling systems.

Criteria	1D model	2D model	CTTC	RayMan	SOLWEIG	Fluent	TownScope	ENVI-met 3.1
Computation time	✓	✓	✓	✓	✓	×	✓	×
Considering urban geometry	×	✓	✓	✓	✓	✓	✓	✓
Predefined assumptions	✓	✓	✓	×	×	×	×	×
Including vegetation scheme	✓	✓	✓	×	×	✓	✓	✓
Forcing meteorological parameters	×	×	×	✓	×	×	×	×
Limited thermal indices	✓	✓	✓	✓	×	✓	✓	×
Spatial resolution	×	×	×	×	×	✓	×	✓
Limited inputs to generate meaningful outcomes	×	×	×	×	×	×	✓	✓
Calculation of Tmrt	×	×	×	✓	✓	✓	✓	✓

Table 2

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Table 2. Results of previous validation studies that used ENVI-met.

Purpose of investigation	Limitation of ENVI-met	Validated ENVI-met	Reference	Location
To assess the efficiency of green infrastructure in addressing the potential overheating problem in cold-climate urban agglomerations	ENVI-met overestimated and underestimated the air temperature values during night-time and daytime, respectively.	Modifications were needed.	[19]	Glasgow, UK
To investigate the thermal performance characteristics of unshaded courtyards in hot and humid climates	ENVI-met exhibited a high level of agreement between the recorded and modelled meteorological values.	Modifications were needed.	[69]	Malaysia
To assess thermal comfort in different urban tissues	ENVI-met underestimated the values of air temperature by disregarding the regional climate effects.	Modifications were needed.	[83]	São Paulo, Brazil
To measure the effect of landscape on microclimate variation	ENVI-met achieved a reasonable agreement between the simulated and field data on air temperature with a coefficient factor of 0.8087.	Yes	[357]	Beijing, China
To assess the cooling effect of trees and cool roofs on a residential neighbourhood	ENVI-met showed RMSE of 1.41 °C (mesic), 1.81 °C (oasis) and 2.00 °C (xeric) for air temperature at 2 m above the ground level.	Yes	[367]	Phoenix, United States
To assess the effect of various building geometries in four typical urban districts on outdoor temperature and comfort	ENVI-met underestimated the air temperature and overestimated the relative humidity for daytime and night-time. The numerical values of the material properties for the simulation were unified and assumed. The actual cloud coverage was ignored in the model, the effect of horizontal long-wave fluxes was ignored and large time steps (10 min) were used to update the sun position and radiative fluxes from the sky. After adjustments, the coefficient values for air temperature and relative humidity reached 0.78 and 0.7, respectively.	Modifications were needed.	[368]	Montreal, Canada
To investigate the effect of adding shading trees on the street canyon	ENVI-met overestimated the solar radiation for the São Paulo condition. Therefore, solar radiation was reduced to 90%. This discrepancy was attributed to the application of the same material for all buildings and the absence of heat storage in building properties. After minor modifications, the coefficient factor between the measured and simulated values (based on 79 values) was improved to 0.7487.	Modifications were needed.	[275]	São Paulo, Brazil
To evaluate the effect of trees and ground material modification on maximizing the cooling effect and mitigating the heat island effect	ENVI-met underestimated the average values of air and surface temperature. Therefore, the initial temperature was increased by 2 °C to achieve improved correlation between the measured and simulated values. The average wind speed changed from 2.1 to 1.1 m/s because the measured wind speed and direction varied strongly during the day.	Modifications were needed.	[364]	Malaysia
To simulate outdoor air temperature, mean radiant temperature, wind speed, and relative humidity	The variations in the measured and modelled air temperature were similar, and their final correlation coefficient was 0.80 after the adjustment.	Modifications were needed.	[362]	Netherlands

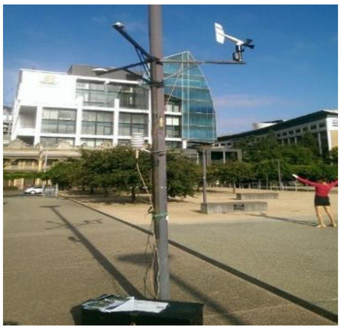
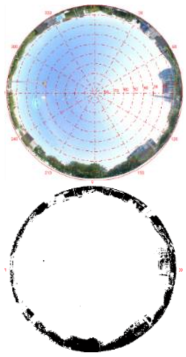
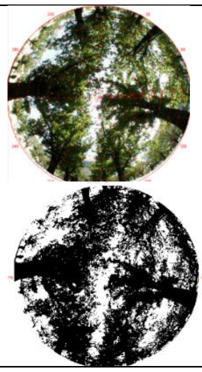
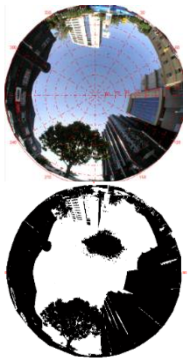
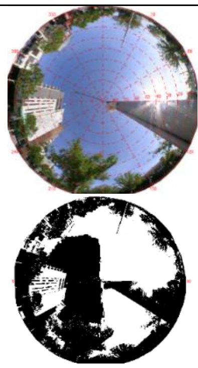
To evaluate the microclimate of an outdoor urban form	ENVI-met underestimated Tmrt after sunset hours because of the reduced short-wave radiation after sunset. The lack of heat storage in the building properties in ENVI-met led to daytime overestimation and night-time underestimation of long-wave radiation emitted by walls. After the modifications, the coefficient values for air temperature and Tmrt reached 0.942 and 0.916, respectively.	Modifications were needed.	[365]	Cairo, Egypt
To evaluate the effect of various greening scenarios on microclimate on the block and neighbourhood scales	The regression analysis between the measured and simulated air temperature did not show a reasonable agreement (R^2 = 0.56). The model did not allow for variations in building envelope, U values or internal temperatures for individual buildings. The model also did not allow forcing of weather variables. The model had a long running time.	Modifications were needed.	[358]	Manchester, United Kingdom
To assess the effect of greening on lowering the ambient air temperature at the pedestrian level	Air temperature, relative humidity, wind velocity and solar irradiance were validated at 12 points by using on-site measurements. ENVI-met overestimated solar irradiance. The spatial and temporal differences were not recorded during the field measurement. Therefore, a cloudless sky was selected as the weather condition for a simulation day, leading to the deviation between the measured and simulated solar values.	Modifications were needed.	[369]	Japan
To evaluate the effect of landscape elements on thermal comfort for detached buildings	ENVI-met tended to slightly overestimate the solar radiation in the study area, thereby reducing the solar radiation to 85%. Some deviations were also recorded between the simulated and field data. Therefore, the input values, including initial atmospheric temperature, soil, wind speed at 10 m above ground level, and specific and relative humidity, were adjusted.	Modifications were needed.	[370]	Damascus, Syria
To simulate near-ground air temperature in a typical residential neighbourhood	ENVI-met achieved a reasonable agreement between the simulated and field data for air temperature 2 m above ground.	Yes	[21]	Phoenix, US
To evaluate the effect of downtown greening on microclimatic data	ENVI-met achieved a reasonable agreement between the measured and simulated data for air temperature (R^2 = 0.745) and Tmrt (R^2 = 0.615).	Yes	[371]	Hong Kong
To investigate the effect of urban design strategies on pedestrian thermal comfort	The discrepancy between the measured and simulated values could be attributed to the non-nested model boundary, the constant values of the potential temperature and humidity at 2,500 m above ground during the simulation without external forcing for the meteorological data as well as the lack of thermal mass in the building properties.	Modifications were needed.	[274]	Shanghai, China
To assess the effect of vegetation on temperature reduction during extreme heat events	The simulation depended on validating air temperature by collecting data from Phoenix, United States, with vegetation and microclimatic conditions similar to those in the study area.	Yes	[288]	Phoenix, US
To evaluate the effect of seven greenspace scenarios on microclimate	In some receptors, a large temperature difference was observed between the measured and simulated temperatures. According to the ENVI-met documentation, at least three nesting grids and five empty grids were required for a large modelling domain. Soil humidity, upper temperature and middle temperature were changed according to a previous study [62]. Given that the model version used in this study was limited to starting temperature and wind condition, the values could not be forced during the simulation.	Modifications were needed.	[358]	Manchester, UK

To assess the effect of street orientation on prevailing winds and its consequences on ventilation and wind speed at the pedestrian level	The measured and simulated values were consistent ($R^2 = 0.80$) for wind speeds below 2 m/s. However, ENVI-met overestimated the wind speed within the canyon for input wind speeds over 2 m/s ($R^2 = 0.70$).	Modifications were needed.	[366]	Curitiba, Brazil
To explore the effects of architectural design on thermal performance in outdoor environments	An insignificant difference was observed between air temperature and wind speed across canyons because of limited thermal heat storage in buildings.	Modifications were needed.	[39]	Algeria

Table 3. Characteristics of selected points for on-site measurement [72].

Point	Site characteristic	SVF value	Surface type	H/W	Height of measurement	Equipment used	Symbol
1	Open space	0.9	Asphalt	–	3 m	Portable weather station	△
2	Under a tree canopy in a park	0.2	Grass	–	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	●
3	E–W-oriented street canyon	0.5	Asphalt	0.5	2 m	HOBO data logger	◣
4	NW–SE-oriented street canyon	0.8	Grass	0.8	2 m	HOBO data logger	◣
5	NW–SE-oriented street canyon	0.4	Asphalt	2.7	2 m	HOBO data logger	◣
6	N–S-oriented street canyon	0.6	Asphalt	0.4	2 m	HOBO data logger	◣
7	Under a tree canopy in a street	0.3	Grass	1.4	0.1 m 0.6 m 1.1 m 1.7 m	Comfort cart	●

Table 4. Selected canyons and SVF images of measurement points.

Point	Selected canyon	SVF image
Point 1		
Point 2		
Point 3		
Point 4		

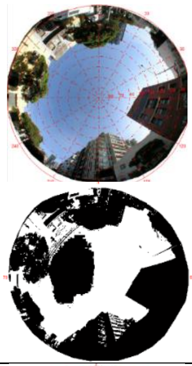
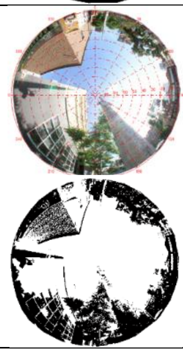
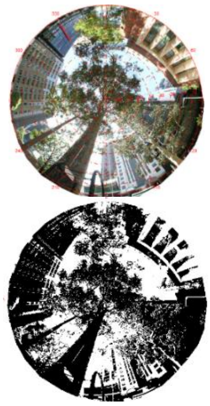
Point 5		
Point 6		
Point 7		

Table 5

Table 5. Differences in measured data at various measurement points during daytime and night-time.

Climatic parameter	Min		Max		(Max−Min)	
	Day	Night	Day	Night	Day	Night
Air temperature (°C)	24.5	19.8	29.6	20.5	5.1	0.7
Relative humidity (%)	45	83.3	58	87.2	13	3.9
Wind speed (m/s)	0.3		2		1.7	

Table 6

Table 6. Initial set-up of model domain (area input file) [72].

Input setup	Value
Orientation (degree from the north)	7
Number of x grids	230
Number of y grids	230
Number of z grids	30
Size of grid cell in m (dx)	3
Size of grid cell in m (dy)	3
Size of grid cell in m (dz)	2
Name of location	Melbourne, Australia
Position on earth	Latitude (−37.49), longitude (144.58)
Number of nesting grids	5
Soil profile for nesting grids	Soils A and B = Loamy soil

Table 7
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Table 7. Settings for configuration file used to run the initial ENVI-met model [72].

Input for configuration file	Value
Start simulation	1:00, January 6, 2015
Total simulation time in hours	48 h
Save model state (each min)	60
Wind speed at 10 m above ground (m/s)	1.7
Wind direction	171
Roughness length	0.1
Initial temperature atmosphere	297 K
Specific humidity at 2,500 m above ground level	9.5
Relative humidity at 2 m%	57
Factor of short-wave adjustment	0.5
Soil data	
Initial temperature, upper layer (0–20 cm) (K)	293
Initial temperature, middle layer (20–50 cm)(K)	293
Initial temperature, deep layer (> 50 cm) (K)	293
Relative humidity, upper layer	30
Relative humidity, middle layer	60
Relative humidity, deep layer	60
Receptor data	
Save receptor (each min)	60 min
Building data	
Inside temperature	19.85 °C
Heat transmission of walls	1.94
Heat transmission of roofs	6
Albedo walls	0.2
Albedo roofs	0.3

Table 8

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Table 8. RMSE values between initial ENVI-met model and measured air temperature at different measurement points.

Simulations	RMSE at selected points						
Points	1	2	3	4	5	6	7
RMSE (measured/initial ENVI-met model)	1.42	1.26	3.14	3.55	5.25	4.62	2.40

Table 9
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Table 9. Input parameters in configuration files used in various simulation runs [72].

Symbol	Changing parameter	In initial ENVI-met model	In adjustment tests
◇	Factor of short-wave adjustment	0.5	1
+	Initial air temperature	297 K (23.8 °C)	295
✸	Relative humidity	57	55
o	Roughness length	0.5	0.1
□	Wind	1.7	4
▽	Albedo walls	0.2	0.3
✡	Albedo roof	0.2	0.4

Table 10
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Table 10. RMSE values in different runs of initial ENVI-met model with altered configuration files.

Symbol	Simulations	RMSE values at selected areas						
		1	2	3	4	5	6	7
×	Initial ENVI-met model	1.42	1.26	3.14	3.55	5.25	4.62	2.40
◇	Factor of short-wave adjustment	1.13	1.66	2.01	2.65	3.64	3.32	0.99
+	Initial air temperature	0.95	0.76	2.85	3.28	4.90	4.30	1.66
✸	Relative humidity	0.95	0.75	2.85	3.28	4.90	4.32	1.69
○	Roughness length	1.28	1.69	2.28	2.73	3.62	3.72	1.38
□	Wind speed	1.14	1.61	2.13	2.65	3.6	3.56	1.11
▽	Albedo of walls	1.14	1.68	2.01	2.65	3.62	3.31	1
✡	Albedo of walls	1.17	1.71	2.06	2.65	3.60	3.31	1.01

Figure 1
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Figure 1. Location of selected points for on-site measurement

Source: [70]

Figure 2

Click here to download Figure: Figure 2.docx

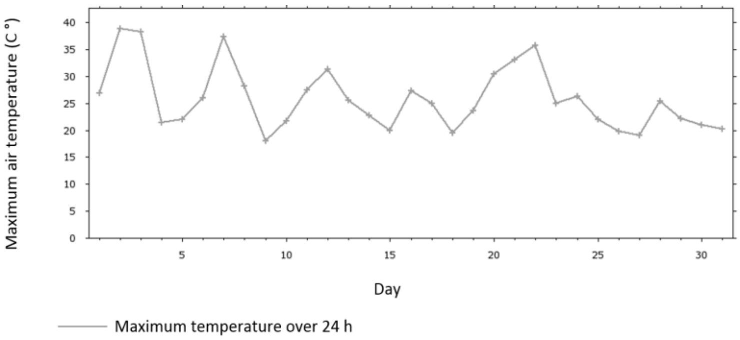

Figure 2. Maximum recorded air temperatures at Melbourne Olympic Park (Station number: 086338) in January 2015, Source: [71].

Figure 3
Click here to download Figure: Figure 3.docx

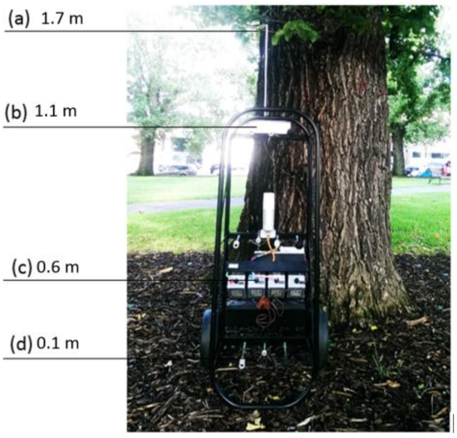

Figure 3. Comfort cart at point 2 under a shade of a tree canopy in an urban park (University Square).

Figure 4
Click here to download Figure: Figure 4.docx

Figure 4. Comfort cart at point 7 under a shade of a tree canopy on Victoria Street.

Figure 5
Click here to download Figure: Figure 5.docx

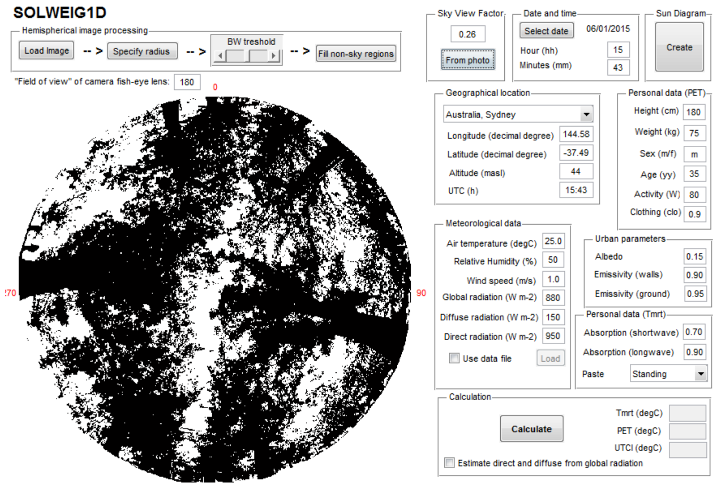

Figure 5. Calculating SVF value from fisheye camera images in SOLWEIG 1D.

Figure 6

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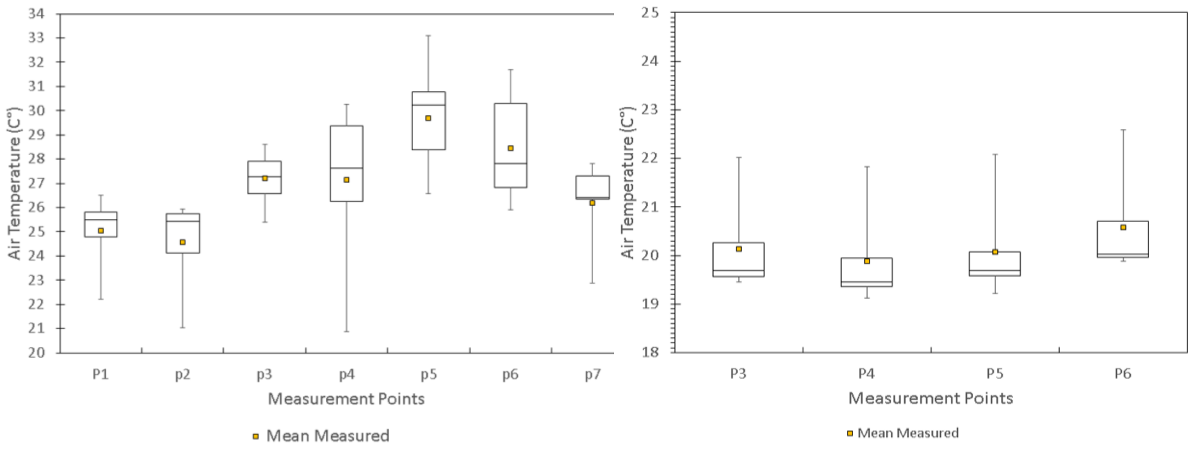

Figure 6. Monitored air temperature at selected measurement points during daytime (9:00–17:00) (left) and night-time (22:00–5:00) (right).

Figure 7

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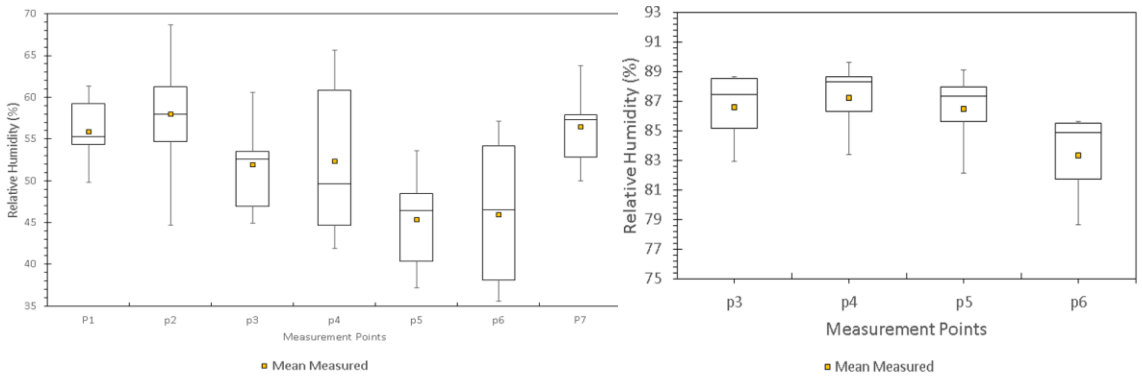

Figure 7 Monitored relative humidity at selected measurement points during daytime (9:00–17:00) (left) and night-time (22:00–5:00) (right).

Figure 8
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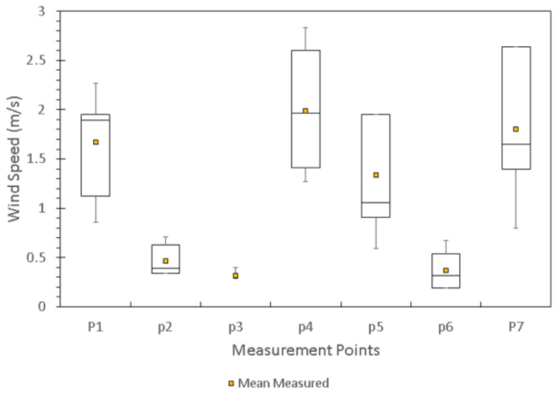

Figure 8 Monitored wind speed at daytime (9:00–17:00).

Figure 9
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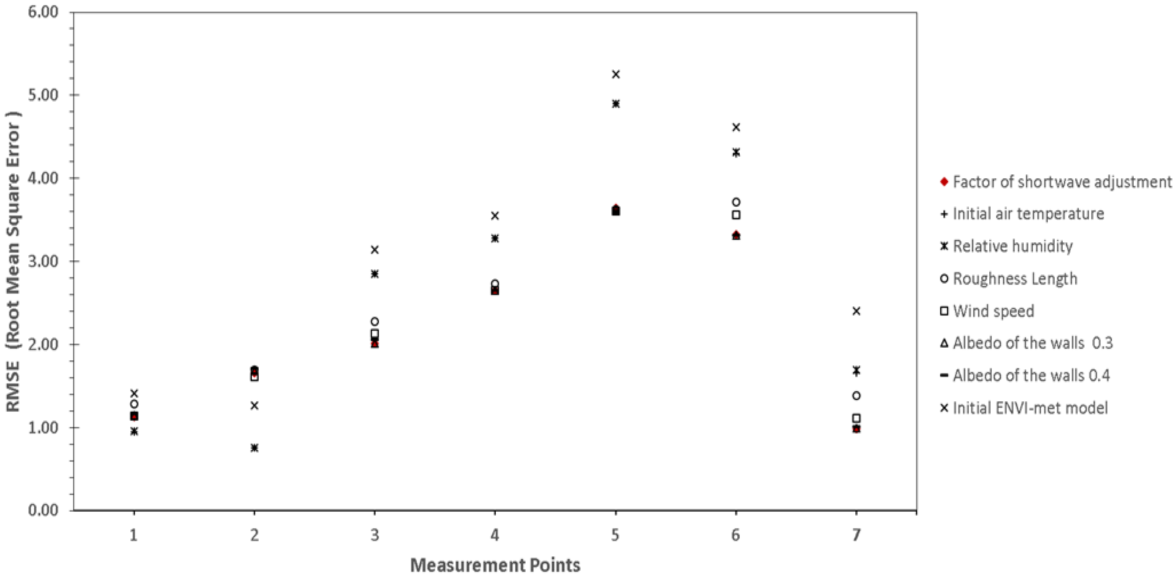

Figure 9 Calculated RMSE in different runs of initial ENVI-met model.

Figure 10
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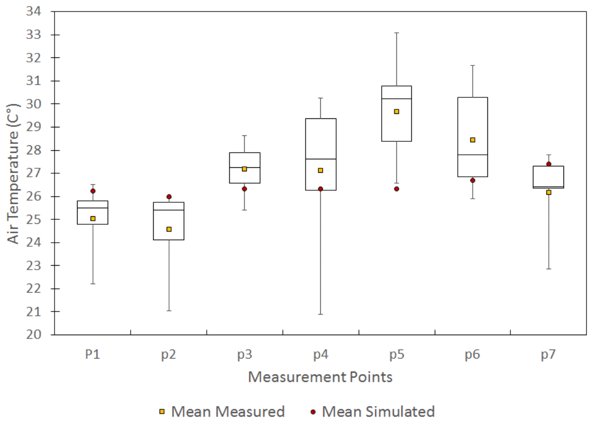

Figure 10 Mean measured and mean simulated value after adjustment.